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Evaluation of Ethanol and Water Introduction via Fumigation on Efficiency and Emissions of a Compression Ignition Engine Using an Atomization Technique

Grant S. Janousek
University of Nebraska at Lincoln, gjanousek@gmail.com

EVALUATION OF ETHANOL AND WATER INTRODUCTION VIA FUMIGATION ON EFFICIENCY AND EMISSIONS OF A COMPRESSION IGNITION ENGINE USING AN ATOMIZATION TECHNIQUE

By

Grant S. Janousek

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Evaluation of Ethanol and Water Introduction via Fumigation on Efficiency and Emissions of a Compression Ignition Engine Using an Atomization Technique

Grant S. Janousek, M.S.

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Advisor: Roger Hoy

Performance of a diesel engine, equipped for ethanol and water fumigation, was studied. The method implemented allowed for non-destructive introduction of liquids in advance of the turbocharger. Engine torque, speed, emission components, diesel and ethanol fuel rates were recorded and analyzed for each mixture of inputs. Based on the results of the study, thermal efficiency was not significantly different from the baseline diesel performance when using several ethanol and water mixtures. On the other hand, ethanol fumigation caused a significant reduction in NOx emissions and an increase in HC and CO emissions. No significant changes in CO_2 or O_2 occurred.

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1 Introduction

1.1 The Need For A Fumigation Study

Diesel (compression ignition) engines are widely used in the world as power sources in off-road and on-road vehicles, electrical generators, irrigation pumps, and numerous other stationary engine applications. Diesel engines have faced significant regulatory challenges with regard to emissions by the United States Environmental Protection Agency (EPA) as well as by international regulatory bodies. In the United States, the Clean Air Act (CAA) authorized the EPA to develop emissions standards. The EPA provides maximum allowable emissions for non-methane hydrocarbons (NMHC), nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter (PM). These emission components are limited as they have been found to be harmful to the atmosphere and to human health (Environmental Protection Agency 2004). The emissions of NOx, HC, CO_2, and CO were studied in this research. A chart of EPA emissions regulations and trends is shown in Appendix A. Allowable NOx emissions are in the process of being cut from 9.2 g/kWh to 0.4 g/kWh over the period of 1997 to 2014 for most diesel engines (Gui et al. 2010).

Different technologies have been developed to reduce emissions. One common strategy is selective catalytic reduction (SCR) which employs urea to reduce NOx emissions. Two issues with urea are its corrosiveness and high temperature freezing point (Kass et al. 2003). The purpose of this research was to evaluate the capability of fumigating ethanol and water with minimal engine modifications to reduce NOx, as an alternative to SCR.

1.2 Objective

The objective of this study was to evaluate the effects of ethanol and water fumigation on thermal efficiency, engine emissions, and overall engine performance using a modern industrial diesel engine typically used for irrigation applications. Ethanol mixtures of 60% alcohol by weight (60ABW), 80ABW and 100ABW were used. The ethanol replaced 5, 10 and 15% of the energy content of diesel by mass (kJ/kg). A water fumigation study was completed to evaluate the effects of water only on the combustion process. This study also evaluated the effect of fumigation, in advance of the turbocharger, on turbine compressor blade deterioration.

2 Literature Review

2.1 NOx Formation

NOx is a grouped emission composed of nitric oxide (NO) and nitrogen dioxide (NO_2). NO is the majority of NOx emissions inside the engine cylinder (Heywood 1988). The two species are grouped together because NO oxidizes to form NO_2 in the environment. NO_2 is the more troubling pollutant, because in the presence of hydrocarbon emissions with ultra violet light, photochemical smog is formed (Stone 1999a).

NOx formation is complex chemically and physically (by means of engine operation). All emissions, especially NOx, vary with engine operating conditions such as injection timing, load, engine speed and Fuel to Air (F/A) ratio (Stone 1999a).

Three mechanisms are involved in the formation of NOx: thermal, prompt and nitrous oxide, also named N_2O-intermediate mechanism (Turns 2006). The thermal mechanism consists of the Zeldovich mechanism and the third equation added by Lavoie. The following is the thermal mechanism:

$$O + N_2 \leftrightarrow NO + N$$

$$N + O_2 \leftrightarrow NO + O$$

$$N + OH \leftrightarrow NO + H$$

The rate constants for these chemical equations are relatively slow compared to combustion rate constants until the temperature reaches 1800 Kelvin. Clearly, NOx formation is dependent on temperature (Stone 1999a).

NO is formed in the flame (Stone 1999a). This is described by the prompt mechanism:

$$CH + N_2 \rightarrow HCN + N$$

"The prompt mechanism is significant when there is fuel bound nitrogen or when the combustion temperatures are so low as to make the thermal mechanism negligible" (Stone 1999a). NO is also formed in post-flame gases, which dominates flame-front produced NO (Heywood 1988).

The N_2O-intermediate mechanism is as follows:

$$N_2 + O + M \leftrightarrow N_2O + M$$

$$H + N_2O \leftrightarrow NO + NH$$

$$O + N_2O \leftrightarrow NO + NO$$

"M" is a "third-body collision partner". The N_2O-intermediate mechanism is significant at low combustion or cylinder temperatures (Turns 2006).

2.2 NOx Reduction Techniques

2.2.1 Engine Control

The EPA finalized a rule to further reduce emissions by implementing engine and fuel control systems (Environmental Protection Agency 2010). For engine and fuel control, an engine control unit (ECU) can be used which contains software and hardware to monitor and control the engine functions. Many changes over the years have occurred, mainly the addition of a sophisticated ECU to control the engine electrical components such as injectors and their timing, fuel quantity, air-to-fuel ratio, exhaust gas recirculation valves and other devices which may affect engine performance and emissions. The ECU is an important engine component in reducing emissions (Deere & Co. 2009).

2.2.2 Injection

Diesel engine injector design and control can play a role in decreasing emissions. Often injectors are supplied with fuel at a high pressure by means of a fuel rail. This type of injection system is commonly called a high pressure common rail (HPCR) system. HPCR along with fuel injectors with small nozzle holes can also be used to control particulate matter, but a reduction of PM can lead to an increase in NOx (Kaneko et al. 2005). An increase in fuel pressure leads to a more efficient combustion, helping to reduce NOx and PM (Deere & Co. 2009).

Historically fuel injection was controlled by mechanical means. To meet the emission requirements, a precise fuel injection quantity is needed along with a start of injection (SOI) (Bosch 2007b). Electronic unit injectors (EUI) can be used to create multiple injections (Gui et al. 2010). Multiple injections can be used to lower combustion temperatures, NOx and PM emissions, and also reduce engine noise, commonly described as diesel engine knock (Deere & Co. 2010).

Spray tip regions of high pressure injectors were studied in Japan. Experimental and numerical work showed that a significant cause of NOx formation is a result of a "weak mixing intensity in the spray tip region" immediately after SOI. With little mixing of air, burned gases have turbulence, staying in the flame tip region of an unsteady flame which is a concentrated high temperature region. NOx forms in these high temperature regions. An unsteady flame is shown in Figure 1. A continuous jet flame or steady flame can reduce NOx. Burned gases pass through the flame tip with little residence time for NOx to form. Figure 1 also shows a view of a steady flame. Obtaining a steady flame was experimentally found by two methods. Injecting inert gases prior to the diesel injection can change the velocity profile, creating a flame similar to a steady flame. Another successful way to reduce NOx by flame control is injecting water before the diesel injection. This leads to the burned gases diffusing through the flame tip region (Kaneko et al. 2005).

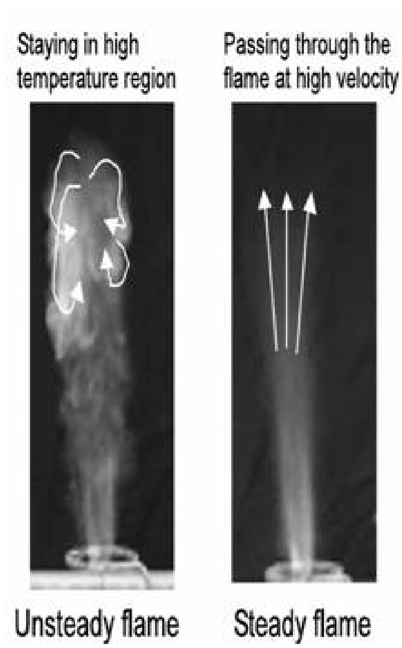

Figure 1. Unsteady flame vs. steady flame (Kaneko et al. 2005).

2.2.3 Exhaust Gas Recirculation

Exhaust gas recirculation, commonly known as EGR is used as a NOx reduction tool. An EGR valve allows a portion of the exhaust gases to mix with fresh intake air to re-enter the cylinder during the engine's intake stroke. EGR displaces some oxygen to lower the combustion temperature to give a significant reduction in NOx. This technique is mainly used in low load, low speed conditions. According to Stone (1999a), "5-10% EGR is likely to halve NOx emissions".

The exhaust gases are often cooled in an intercooler prior to entering the engine cylinders. This is called cooled EGR (Deere & Co. 2009). Cooled EGR decreases NOx production further. A disadvantage of cooled EGR is an increase in the ignition delay period which can increase combustion noise (Stone 1999b).

2.2.4 Advanced Turbocharging

Used with an EGR valve, advanced turbocharging can assist in NOx reduction. A turbocharger with variable geometry may be used in conjunction with an EGR valve to regulate the amount of exhaust gas that enters the cylinder. A variable-geometry turbocharger (VGT) is electronically controlled to change the pitch of its vanes. A VGT allows the engine to maintain boost pressure at low engine loads and speeds (Deere & Co. 2009).

Series turbocharger technology is used as the amount of EGR increases. NOx is decreased with an increase in EGR, but a higher intake pressure is required (Deere & Co. 2009). Similar to a VGT, a series turbocharger arrangement will maintain boost pressures with EGR.

2.2.5 NOx Specific Aftertreatment Systems

Selective catalytic reduction (SCR) is a technology that lowers NOx (Kass et al. 2003). Two reducing agents that have been studied are urea and ethanol.

Urea is used as a reducing agent (also called a reductant) but is first hydrolyzed to produce ammonia. Ammonia (NH_3) can be used directly to achieve NOx reduction but this is not a desirable practice because of corrosion and health hazards.

The following two chemical reactions show the production of ammonia (Bosch 2007a):

$$(NH_2)_2CO \rightarrow NH_3 + HNCO$$

$$HNCO + H_2O \rightarrow CO_2 + NH_3$$

The first reaction is thermolysis where ammonia and isocyanic acid are formed. The isocyanic acid combines with water to form more ammonia in a reaction called hydrolysis.

The ammonia reacts in a catalyst to convert NOx into nitrogen and water (Bosch 2007a):

$$4NO + 4NH_3 + O_2 \xrightarrow{catalyst} 4N_2 + 6H_2O$$

$$NO + NO_2 + 2NH_3 \xrightarrow{catalyst} 2N_2 + 3H_2O$$

$$6NO_2 + 8NH_3 \xrightarrow{catalyst} 7N_2 + 12H_2O$$

Typical SCR systems can convert more than 80% of the NOx emissions while the urea consumption ranges from 2-5% of the diesel flow rate. One addition to an SCR system is a catalyst to catch NH_3 that has not been converted (commonly called ammonia slip). A typical SCR configuration is shown in Figure 2.

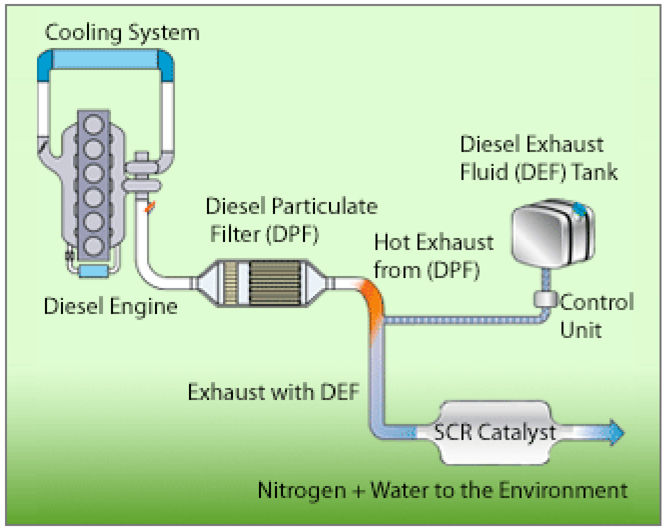

Figure 2. Typical SCR schematic (Diesel Technology Forum n.d.).

The following are problems associated with using urea as a reducing agent (Kass et al. 2003):

- Need a separate urea storage tank
- Need a urea delivery system with sophisticated controls
- Residue build up from over injection or injection at low temperatures
- Urea is corrosive
- Urea has a high freezing temperature

The urea fluid used commercially in the on-road industry and starting to emerge in the off-road industry is called diesel exhaust fluid (DEF) (AGCO Corporation 2010). DEF is composed of 32.5% urea with the remainder being water. Its freezing temperature is -11^{o}C (Gui et al. 2010).

Because of the issues with urea listed above, researchers have examined other reducing agents, especially those composed of hydrocarbons. Alumina supported silver catalysts work well with alcohols, paraffins, and aldehydes as reducing agents (Kass et al. 2003).

Research was conducted at the National Transportation Research Center to evaluate the reduction of NOx using ethanol as a fuel born reducing agent. The experiment focused on two types of ethanol reducing agents. One was created from an emulsified mixture of diesel and ethanol (E-diesel). The E-diesel was composed of 15% ethanol by volume, 1.5% blending agent and 83.5% low sulfur diesel. The ethanol from the E-diesel was separated by distillation on-board the engine. The diesel burned in the cylinder while the distilled ethanol was injected into the exhaust before a catalyst. The second type of ethanol reducing agent was fuel grade ethanol. The results showed no difference in NOx reduction between the two reducing agents. Final results showed that the NOx conversion efficiency was 85-95% (Kass et al. 2003).

A similar study was done in China. Ethanol was added directly into the exhaust stream before a silver catalyst, specifically Ag/Al_2O_3. NOx reduction was up to 90% (Dong et al. 2008).

Typical catalysts used for engine exhaust reduce HC and CO emissions (Hoelzer et al. n.d.). New catalysts have been developed to reduce NOx emissions. NOx Storage Catalysts (NSC) can store NO_2 but not NO. The NO is oxidized before the NSC.

An example of a storage material used is barium carbonate ($BaCO_3$). The NSC can only store NO_2 for a period of time and then requires a regeneration which is commanded by the ECU on a time basis. The ECU modifies engine operating conditions to create rich exhaust (excess air ratio is less than 1). The reducing agents such as CO, H_2 and some HC from the rich exhaust release NO_2 from storage to be converted into N_2 by the catalyst (Bosch 2007a). Regeneration occurs for only a few seconds.

2.3 Past Fumigation Results

Fumigation is the process of introducing atomized fuel into the air intake of an engine (Abu-Qudais et al. 2000). There are numerous systems on the market for engine fumigation such as Coolingmist LLC (Coolingmist LLC n.d.) and Snow Performance (Snow Performance 2006), most of which are for performance enhancement. Fumigation has been a known performance enhancer since the early 1940's, where it was implemented as a power boosting system in numerous German war aircraft (Gunston and Bridgman 1994). Most literature showed that fumigation has not been researched for their emission reducing characteristics until the 1980's. New interest has been sparked in using fumigation to reduce NOx. Two systems are dominant, using either methanol or ethanol as fumigants.

Fumigation of engines reduces NOx because the flame temperature in the cylinder is decreased (Jiang et al. 1990). Decreasing the cylinder temperature also increases the density of the air which improves engine performance. Another incentive to use fumigation is that it requires minimum engine modification (Abu-Qudais et al. 2000).

2.3.1 Methanol Fumigation with a Diesel Oxidation Catalyst

A methanol fumigation study, using a diesel oxidation catalyst (DOC), was conducted at the Hong Kong Polytechnic University in 2008. The goal of the study was to observe gaseous and particulate emissions from a diesel engine while using methanol fumigation along with a DOC to further decrease the emissions. Methanol was used for its characteristic high latent heat of vaporization. When burned in an engine cylinder, methanol has a cooling effect, lowering cylinder temperatures and lowering NOx.

The test studied the replacement of diesel fuel with methanol. The methanol accounted for 10-30% of the engine loading. An example is fueling the engine with diesel until 90% load and fumigating methanol until the engine reaches 100% load, creating a 10% replacement by load. The methanol was injected into the air intake manifold using one injector for each port, ensuring uniform distribution of the methanol between engine cylinders.

The results without a DOC showed an average of 14.6% reduction in brake specific NOx (BSNOx) with a maximum reduction of 20%. The maximum reduction occurred with 30% fumigation of methanol. It was reported that NO_2 increased with the amount of fumigation. It was found that no change in BSNOx occurred after passing through the DOC. The DOC reduced brake specific hydrocarbons, brake specific CO and brake specific NO_2 from medium to high engine loadings (Zhang et al. 2009).

2.3.2 Ethanol Fumigation

In the early 1940's, power boosting systems were developed for German aircraft. The Messerschmitt Me 109 aircraft, with a Daimler-Benz DB 605 AM engine, was equipped with an MW 50 (Methanol-Wasser 50%) system which injected a fuel mixture into the intake side of the supercharger. Fuel mixtures consisted of 49.5 parts of tap water, 0.5 parts of anti-corrosion fluid and the remainder methanol or ethanol. A 4% power increase was obtained with a constant boost pressure using the MW 50 system. Pure water injection also was used on the BMW 323 R and Jumo 213 A engines for an increase in power (Gunston and Bridgman 1994).

Sullivan and Bashford (1981) researched pre-turbocharger fumigation at the University of Nebraska – Lincoln. They reported excessive wear of the turbocharger due to sufficiently large droplets, from the traditional injection nozzles employed, impacting on the compressor blades. The excessive wear was discovered after 30 h of use (Sullivan and Bashford 1981).

Ethanol fumigation was studied at the University of Wisconsin – Madison in 1981. Ethanol was injected into the intake manifold using an atomizing nozzle. Through a preliminary test, "it was found that to avoid liquid droplet impingement on the compressor blades the injector needed to be located downstream of the compressor, in the high pressure section of the inlet manifold." Two ethanol proofs were used: 160 and 200. For the J.I. Case engine used, a problem of uniform ethanol distribution was found because exhaust port temperatures were not the same for the study. Overall, ethanol fumigation decreased NOx and smoke while HC increased (Chen et al. 1981).

The U.S. Department of Energy conducted a test to evaluate the emissions, efficiency, and durability of agricultural diesel engines using ethanol in 1983. A 160 proof ethanol mixture was used with a 25% substitution. HC and CO increased while NOx showed similar values to that of diesel. A 500 h durability test also was completed on three engines: two with fumigation and one with a mechanical fuel (diesel and ethanol) emulsifier. After an engine tear down, no deterioration was shown on the two engines using the fumigation method. The two engines showed "exceptionally clean combustion zones, piston ring areas and exhaust valves." The engine using an emulsified fuel had a premature engine failure (Allsup 1983).

Shropshire and Bashford (1984) compared various ethanol fumigation systems using nozzles downstream of the turbocharger. Thermal efficiency was maintained at high loads but decreased at low loads. Air atomizing nozzles that created a fine spray caused engine knocking. Multiple nozzles used in the intake manifold provided better results than a single nozzle (Shropshire and Bashford 1984).

Walker (1984) studied the performance of a fumigated diesel tractor engine and found that CO emissions increased at light and heavy loads. Thermal efficiency only increased at light and medium engine loads and at reduced engine speeds. Walker claimed the optimum operating condition was fumigating at part throttle (Walker 1984).

Chaplin and Janius (1987) discovered engine instability when using ethanol fumigation during low speed operation. Brake thermal efficiency was maintained at 2/3 and full load but decreased for 1/3 engine load.

A study at the University of Illinois at U-C in 1988 evaluated the effect of fumigating various ethanol proofs on a diesel engine. Ethanol was injected directly into the intake ports via a multi-point injection system to ensure even cylinder distribution. Ethanol proofs used were 100, 125, 150, 175 and 200. HC and CO significantly increased and was not dependant on ethanol proof. NO was decreased using lower than 150 proof ethanol. Lower proofs reduced the rate of pressure rise in the cylinder (kPa/degree). For the International Harvester engine tested, the optimum ethanol proofs were 100 to 150 (Hayes et al. 1988).

Researchers at Iowa State University studied the effect of alcohol fumigation on diesel flame temperature and emissions in 1990. For fumigation, results showed increases in CO and HC, while NOx is decreased. Another study was performed to evaluate the water's contribution in the mixture. The flame temperature lowered as water in the mixture was vaporized. It also was determined that thermal efficiency was not affected until the water flow rate reached 2.5 times the diesel flow rate (Jiang et al. 1990).

A study at the Jordan University of Science and Technology in 1999 again found that ethanol fumigation used to supplement diesel fuel can significantly reduce principle emission components (Abu-Qudais et al. 2000). It was shown that the optimum ethanol fumigation rate was 20%. Results achieved included: a) 7.5% increase in brake thermal efficiency, b) 55% reduction in CO emissions, c) 36% decrease in HC emissions, and d) 51% reduction in NOx soot mass concentration.

2.3.3 Water Induction In Diesel Engines

Two studies evaluated the effects of introducing water into the cylinders of diesel engines. One study modeled the effect of directly injecting water into the cylinder. Liquid water vaporization and an "increase in specific heat of the gas around the flame" accounted for lower cylinder temperatures (Bedford et al. 2000). The second study used a fumigation method via the air intake. During this study, brake specific fuel consumption was increased. NOx emissions were decreased and were shown to decrease with higher water flow rates (Ryu and Oh 2004).

Little work has been done on fumigation to regulate diesel engine emissions since the boom of the 1980's and the few in the 1990's. The engines in the literature cited did not have the sophistication of today's engines with advanced turbocharging, electronic unit injectors and EGR.

3 Material and Methods

3.1 Test Criteria

3.1.1 Test Design

The overall goal of this research was to determine the effects of ethanol and water fumigation on diesel engine emissions, thermal efficiency and turbocharger compressor blade durability. The test included accurate measurements of emissions, fuel rates, engine speed, dynamometer load, temperatures and pressures.

3.1.2 Location Selection

The Nebraska Tractor Test Laboratory was used for the research. The facilities included an eddy current dynamometer and an exhaust removal system. Personnel were available for instrumentation and troubleshooting needs.

3.1.3 Engine Selection

The test was performed on a John Deere 4.5L Power Tech Plus, 4 valve head, Tier 3 diesel engine (4045HF485, John Deere, Waterloo, Iowa). The engine was provided by Industrial Irrigation in Hastings, Nebraska.

The engine arrived new at the Nebraska Tractor Test Laboratory to be used for experimental purposes. An engine break-in procedure was followed prior to all testing. The break-in procedure consisted of randomly running the engine at 6 engine speeds and varying loads from 60% to 80% for 20 h. The break-in procedure can be found in Appendix B. The engine was used in preliminary ethanol fumigation work, a biodiesel emissions study using B5 and classroom power curve testing for 61.5 h after break-in. The engine had 81.5 h at the start of this test. An engine hour time-line is included in

Appendix C. The engine test set-up is shown in Figure 3 and engine specifications are shown in Table 1.

Figure 3. John Deere 4.5L engine coupled to Dynamatic dynamometer.

Table 1. Test Engine Specifications (John Deere Power Systems 2006)

Engine Make	John Deere
Engine Model	4045HF485
Displacement, L (in^3)	4.5 (275)
ECU P/N	RE520953
Engine Software	72 LJ
Number of Cylinders	4
Cylinder Bore, mm (in)	106 (4.17)
Stroke, mm (in)	127 (5.00)
Compression Ratio	17.0:1
Rated Power	115 kW (154 hp) @ 2400 rpm

3.1.4 Fuels

In this study, the ethanol mixtures were formed using denatured ethanol (E98) and distilled water. An adiabatic oxygen bomb calorimeter (Model 1241, Parr Instrument Company, Moline, Illinois) was used to determine the lower heating values of the fuels used in thermal efficiency calculations. SAE J1498 was used as an aid in heating value calculations (Society of Automotive Engineers, Inc. 1998). Specific gravity was determined using Fisherbrand Precision specific gravity hydrometers (Catalog No. 11-555C, 11-555D, 11-555E, Thermo Fisher Scientific Inc., Waltham, Massachusetts). The lower heating value and specific gravity of each fuel tested is shown in Table 2. Distilled water was used in the water fumigation study.

Table 2. Fuel Specifications

Fuel	**Lower Heating Value** *kJ/kg (BTU/lb)*	**Specific Gravity** *Measured at 20˚C*
#2 Diesel	43436 (18674)	0.845[1]
60ABW	15759 (6775)	0.893
80ABW	21616 (9293)	0.844
100ABW	27140 (11668)	0.791

[1]Value determined by Nebraska Tractor Test Laboratory at 15˚C

The fuels were mixed in 114 L (30 gal.) plastic barrels. The barrels were physically shaken to mix the ethanol and the water. Water was poured first and ethanol last.

When creating the 60ABW mixture, a problem arose. A specific gravity test showed that the results did not agree with the CRC Handbook values (The Chemical Rubber Co. 1973). Mixing a small batch in a graduated cylinder showed what was occurring. The mixture had a high concentration of pure ethanol on the top and pure water on the bottom. The 60ABW mixture was not mixed thoroughly. A photo of the 60ABW in the graduated cylinder is shown in Figure 4.

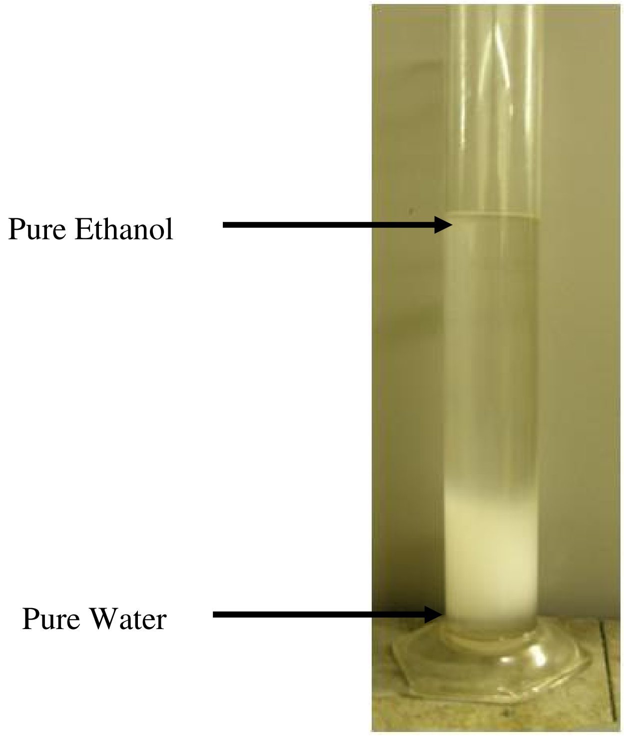

Figure 4. 60ABW mixture not thoroughly mixed.

A solution to fix poor mixing was to place a circulating pump (Model 12-801-1, Holley Performance Products, Inc., Bowling Green, Kentucky) in the 114 L barrels, shown in Figure 5. The fuel mixture was circulated throughout testing to ensure a homogenous fuel.

Figure 5. Ethanol mixture fuel barrel with circulation pump.

3.1.5 Nozzle Description

Fumigating in advance of the turbocharger was chosen because of the simplicity of the system, lack of computer controller and the very fine atomization of the nozzle that was used. Placing the nozzle in advance of the turbocharger allowed the compressor to add additional mixing to the air/fuel mixture. No computer controller or pressure tank was needed to overcome boost pressure downstream of the turbocharger. Further, the nozzle injected fluid against a constant pressure intake air rather than against boost pressure that varied based upon engine operating conditions.

To fumigate in advance of the turbocharger, a proprietary nozzle was employed that used the fluid physics of shear using a low pressure source which was turbocharger boost pressure. This allowed for very fine atomization of the ethanol/water mixture which could be used safely in advance of the turbocharger. The nozzle was supplied with boost pressure from the engine and the fuel mixture from two peristaltic pumps (Masterflex Model 7518-00, Cole-Parmer, Vernon Hills, Illinois). The flow rate of the peristaltic pumps was regulated by a digital controller (Dart Model MDP PRN659D, Dart Controls, Inc., Zionsville, Indiana). The arrangement of the fumigation system is shown in Figure 6.

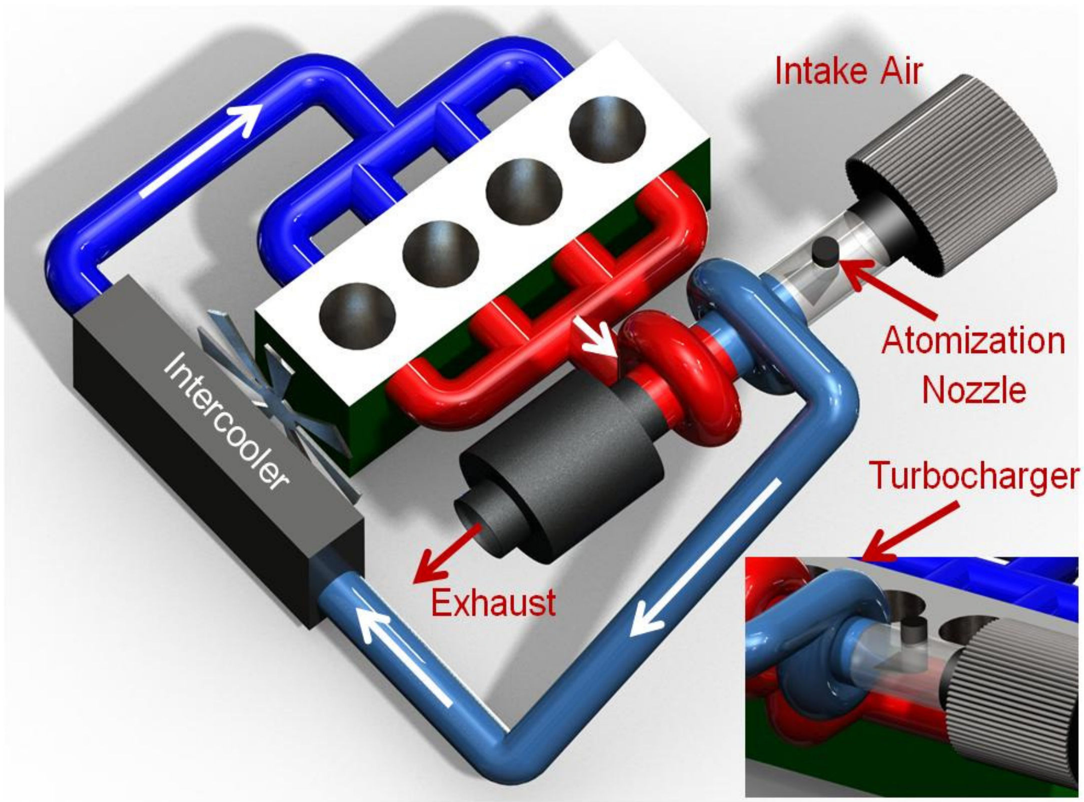

Figure 6. Fumigation system schematic.

The nozzle was located 17.8 cm (7 inches) from the end of the turbocharger casting, where the turbocharger boot slips over the turbocharger casting. This is shown in Figure 7.

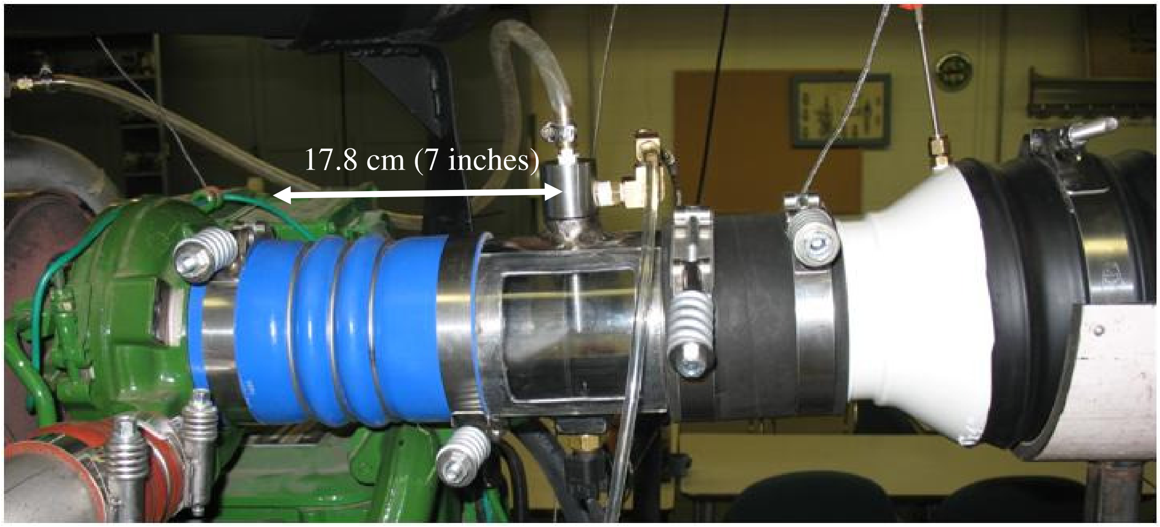

Figure 7. Location of the atomizing nozzle.

3.1.6 Instrumentation

3.1.6.1 Dynamometer And Load Cell

A Dynamatic absorbing dynamometer (Model 1519 D.G., Dyne Systems, Inc., Jackson, Wisconsin) was used to apply load. Rated capacity of the dynamometer was 261 kW (350 hp) at 900 rpm. The load from the dynamometer was measured using a load cell (Model 1110-JW, Interface, Inc., Scottsdale, Arizona) capable of force measurements up to 4,448 N (1,000 lbs).

3.1.6.2 5 Gas Analyzer

A gas analyzer (Model 9005, Bridge Analyzers, Inc., Alameda, California) was used to measure the level of emissions, including CO, CO_2, O_2, HC, and NOx. All emissions channels had a 5% relative accuracy and 3% relative repeatability given by the manufacturer. The analyzer allowed these pollutants to be measured directly on a parts per million (ppm) or percentage basis, but was not suitable for EPA certification. HC were measured with the Hexane C-6 scale. The location of the analyzer probe was after the muffler as shown in Figure 8.

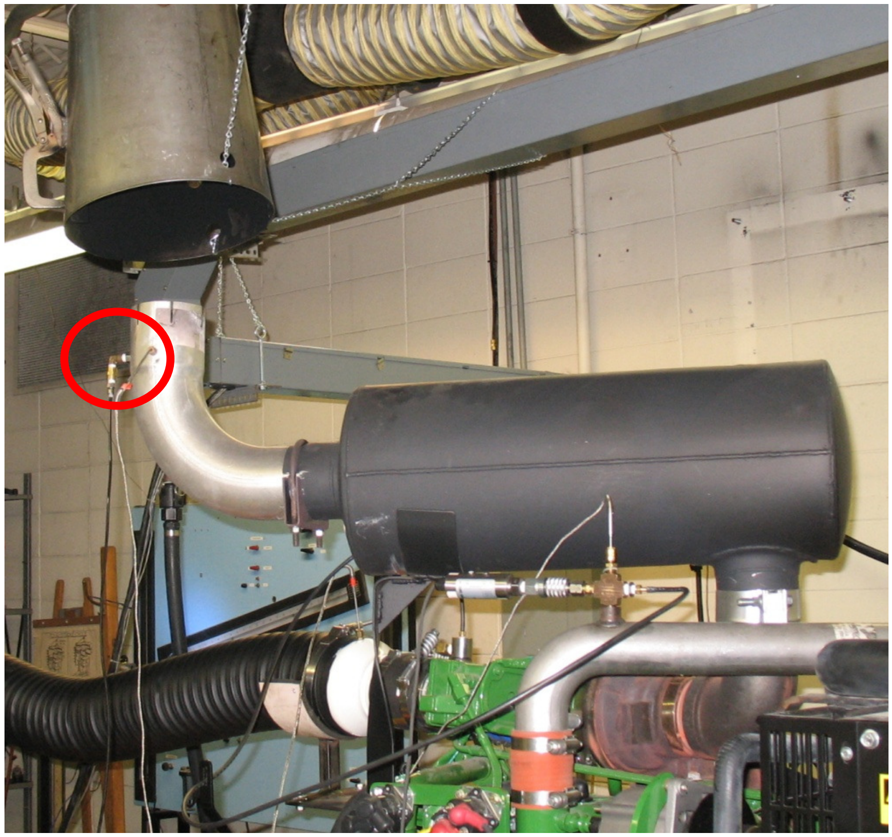

Figure 8. Location of the probe for sampling exhaust gases.

3.1.6.3 Fuel Flow Measurements

A mass flow sensor (Model DS025S119SU, Micro Motion Inc., Boulder, Colorado) was used to measure diesel mass fuel flow. A mass flow sensor (Model CMF010M324NQBMEZZZ, Micro Motion Inc., Boulder, Colorado) was used to measure the ethanol and water mass fuel flows.

3.1.6.4 Temperature And Pressure Measurements

Critical engine temperatures were measured using Type K thermocouples (OMEGA Engineering, INC., Stamford, Connecticut). Temperatures measured were engine intake air, intake flow meter air, exhaust gas, coolant, oil, boost temperature before and after the intercooler, diesel, ethanol and ambient air temperature at the front of the radiator.

Turbocharger boost pressure was measured with a pressure transducer (Model 1000, 0-50 PSIG, Spectre Sensors, Inc., Bay Village, Ohio). Oil pressure was measured with a pressure transducer (Model 1000, 0-100 PSIG, Spectre Sensors, Inc., Bay Village, Ohio).

3.1.6.5 Engine Speed Measurements

A fiber optic sensor (Model D12E2P6FV, Banner Engineering Corp., Minneapolis, Minnesota) was used with a glass fiber optic cable (Model BT23S, Banner Engineering Corp., Minneapolis, Minnesota) to measure dynamometer speed. Since the engine was coupled directly to the dynamometer, engine speed equaled dynamometer speed.

3.1.6.6 Air Flow Measurements

The air intake flow rate was measured so that NOx (ppm) measurements from the gas analyzer could be expressed as brake specific NOx (g/kWh). A venturi (Serial 957003, Badger/Wyatt Engineering LLC, Lincoln, Rhode Island) and an inclined tube manometer (Model 40HE35FF, Meriam Process Technologies, Cleveland, Ohio) were used to measure volumetric air flow rate of the air intake of the engine. Volumetric flow rate was converted to mass flow rate by using the average temperature measured in the air flow meter and average barometric pressure.

3.1.7 Data Acquisition

A data acquisition system using National Instruments hardware and LabVIEW 2009 software (National Instruments, Inc., Austin, Texas) was utilized to collect and record all the measurements. The schematic of the data acquisition set-up is shown in Figure 9. The LabVIEW front panels and block diagrams are located in Appendix D.

With this data acquisition system, up to 14 thermocouples could be monitored using the two SCB-68 boards, 8 counters with the TB-2715 and up to 8 analog inputs with the SCB-100. All transducers connected to the data acquisition system could be read rapidly enough to be considered simultaneous.

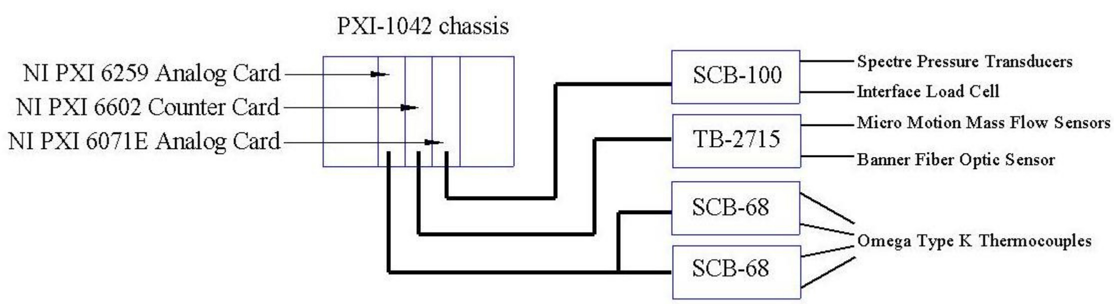

Figure 9. National Instruments data acquisition schematic.

3.2 Test Procedure

A series of baseline tests (without fumigation) were performed to establish "normal" power and torque curves, level of emissions, and fuel consumption. Engine speed selections were chosen from SAE J1312 (SAE, 1995) and a series of typical irrigation pump speeds. SAE J1312 engine speed values were 1450 rpm (maximum torque speed) and 2400 rpm (rated engine speed). Engine speeds that corresponded to common irrigation pump speeds chosen for this study were 1200, 1584, 1760, 1956 and 2200 rpm. At each speed, the engine was loaded to 100, 90, 75 and 50% of the maximum torque as established from the initial 100% load baseline test. The complete test matrix is located in Appendix E. The reduced loads were established to allow interpretation of the results for the range of typical irrigation pumping operations. Verification tests of four engine speeds and loads (percentage of maximum torque at the given engine speed), shown in Table 3, were completed after each ethanol fumigation test to detect any temporal changes in engine performance.

Table 3. Four point engine performance test.

Engine Speed (rpm)	**Load (% of max. torque)**
1200	50
2200	75
1760	90
1450	100

The fumigation process studied in this research involved two experimental designs. The first experimental design involved fumigation of 60ABW, 80ABW and 100ABW ethanol fuel mixtures into the air intake of the engine in advance of the turbocharger. The amount of ethanol fumigated was maintained at increments of 5, 10 and 15% of the energy content by mass with respect to the primary, #2 diesel fuel supply at all times for each ethanol mixture. The energy balance equations can be found in Appendix F. Both engine throttle and ethanol flow rate were controlled manually to maintain the desired replacement rates assigned. The experiment matched the targeted engine speeds and torques determined from the baseline test.

The second experimental design involved a study of fumigating distilled water at the same location in advance of the turbocharger. The engine was loaded to 100% torque and the water mass flow rate was increased to maintain a percentage of diesel mass flow rate. Percentages examined were 3% to 24% of the diesel mass flow rate in increments of 3%. Engine speeds were matched to those of the baseline test but only included 1450, 1956 and 2200 rpm, a subset of the speeds used for the ethanol fumigation study.

The test was conducted at the Nebraska Tractor Test Laboratory using the test protocol adopted from OECD Code 2 (OECD 2009) for tractor and engine testing. All data was collected during steady-state conditions only. Each valid record represented an average of two, two-minute averages that were found to be within 1% of each other in terms of engine speeds, fuel flow rates and torque measurements. The engine start-up and shutdown procedures that were used are found in Appendix G.

Operating errors occurred with the 5 gas analyzer (calibration and operator error leading to data not being recorded). Some tests were repeated at a later time to record emissions. The engine test schedule table in Appendix C shows which tests were repeated. During previous testing, it was found that emissions reached a steady-state value quickly and did not change. The emission retests were modified to run the engine at a steady-state mode for 1 min at each operating point prior to collecting emissions data.

3.3 Data Analysis

The engine data was written to an Excel spreadsheet with the use of LabVIEW with the exception of emissions. Emissions were recorded using the Bridge gas analyzer software (PC Exhaust Analysis Software) which was written as a comma delimited text file. Emission data were combined with the corresponding engine data using the time stamps. All two, two minute averages were averaged to produce one operating condition data set.

SAS 9.2 (SAS Institute Inc. 2009), a statistical analysis program, was used to analyze the data ($\alpha = 0.05$). All of the data was arranged in a Microsoft Excel spreadsheet that was suitable for direct input into SAS. The analysis of thermal efficiency used all 2 min average data. The analysis of emissions used all emissions data that were collected, whether in 2 min averages or the 1 min emissions retests. The water fumigation data was also compiled into a Microsoft Excel spreadsheet for statistical analysis.

The ethanol fumigation experiment was conducted as a randomized complete block strip-split-plot design. The four loads (100, 90, 75 and 50% of the maximum torque) were considered to be random blocks. The whole plots consisted of diesel only and nine treatment combinations: three ethanol mixtures (60ABW, 80ABW, and 100ABW) by three replacement ratios (5, 10, and 15%). The seven speeds were applied in a strip-split plot. The Mixed procedure in SAS software 9.2 (SAS Institute Inc., Cary, North Carolina) was used to analyze the data.

Four different SAS programs were written to analyze the data, which can be found in Appendix H. *Ethanol Emissions Analysis.sas* was SAS code that analyzed all of the ethanol fumigation emissions except hydrocarbons. The data was analyzed using load as a blocking factor. NOx was analyzed in parts per million to avoid the introduction of possible error due to air flow measurements. Hydrocarbons were analyzed using *Ethanol Emissions HC.sas*. *Ethanol Thermal Efficiency.sas* code analyzed the engine thermal efficiencies. *Water Analysis.sas* code analyzed all of the water fumigation results.

The design of the study for water fumigation did not include replication or varying loads. Instead, linear regression was performed on the data using the SAS Proc Reg procedure to determine whether the slope was significant or not; however, the design of the experiment did not allow for a determination of whether or not a specific percentage of water was significantly different from another.

4 Ethanol Fumigation Results

4.1 Emissions Results

4.1.1 NOx

Fumigation of the different ethanol mixtures, using the delivery method that was evaluated, showed a significant decrease of NOx emissions throughout the engine speeds above 1500 rpm. This observation coincided with previous findings which showed potential for a significant reduction in NOx emissions (Abu-Qudais et al. 1999). The expected decrease in NOx may have been caused by lower combustion temperature due to the ethanol-related ignition delay similar to that found in SAE Paper 810680 (Chen et al. 1981).

All mixture/replacement combinations were significantly lower than the diesel only baseline as determined by SAS (p-value <0.0001) when analyzing NOx above 1450 rpm. Further analysis revealed that there was no significant difference in NOx values when comparing all mixtures with a 15% replacement, shown in Table 4. Since the analysis showed that engine load did not significantly affect NOx, in parts per million, a generalized plot could be averaged over all loads. That plot is shown in Figure 10. Note that the 60ABW 15R, averaged over all loads, was lower than the rest because it included fewer points, with the majority being at lower loads. Numerous operating points at higher engine loads of 60ABW 15R exceeded the limitations of the nozzle for the required fluid flow and could not be tested. When the nozzle was at its flow limit, large droplets could form and lead to improper mixing and immediate turbocharger damage.

Table 4. Differences of Least Square Means p-values using SAS

Mix/Replacement Comparisons	p-value	Estimate (ppm)
60ABW 15R - 80ABW 15R	0.0635	-36.08
60ABW 15R - 100ABW 15R	0.0646	-35.92
80ABW 15R - 100ABW 15R	0.9902	0.16

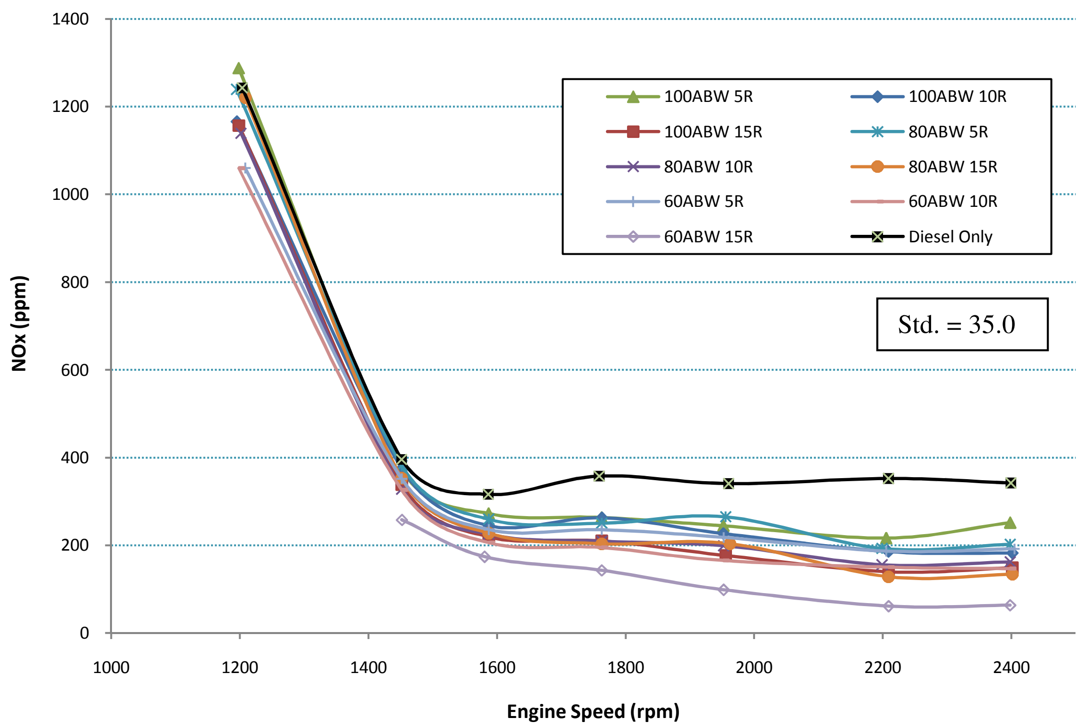

Figure 10. Generalized NOx plot averaged over all loads tested.

The NOx emissions were converted to brake specific NOx in units of g/kWh. The plots at each load are shown in Figure 14. Because of limited data collected for 60ABW 15R, only 2 data points are shown at 100% load and none are shown for 90% load.

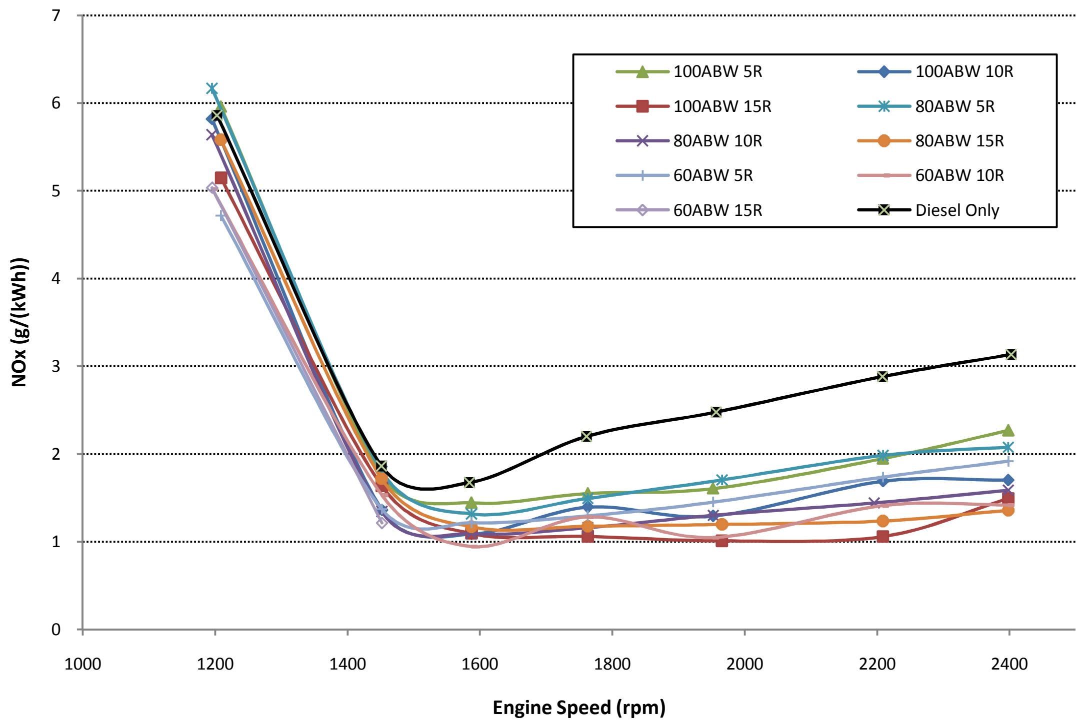

Figure 11. Brake specific NOx emission results (g/kWh) at 100% engine load.

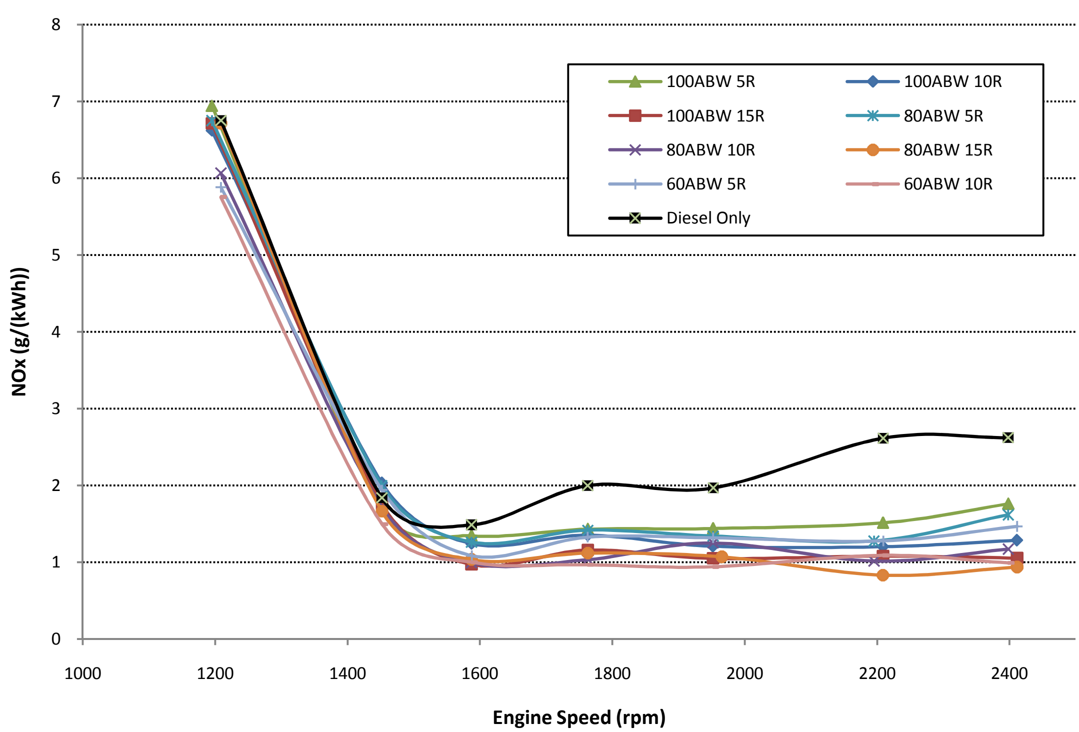

Figure 12. Brake specific NOx emission results (g/kWh) at 90% engine load.

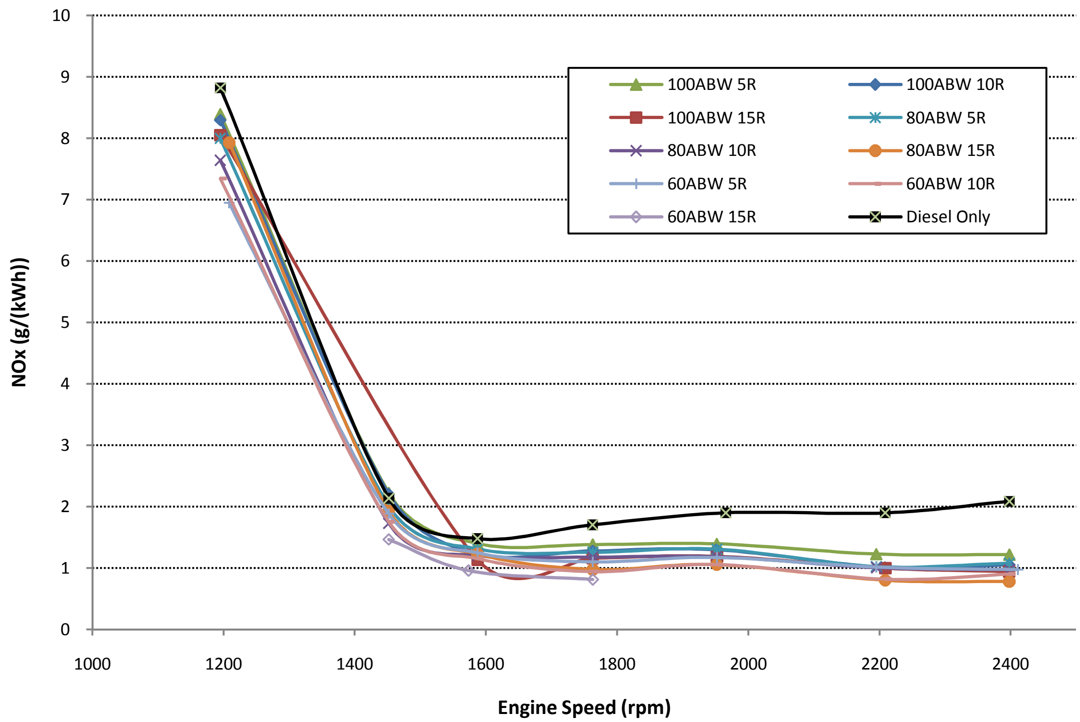

Figure 13. Brake specific NOx emission results (g/kWh) at 75% engine load.

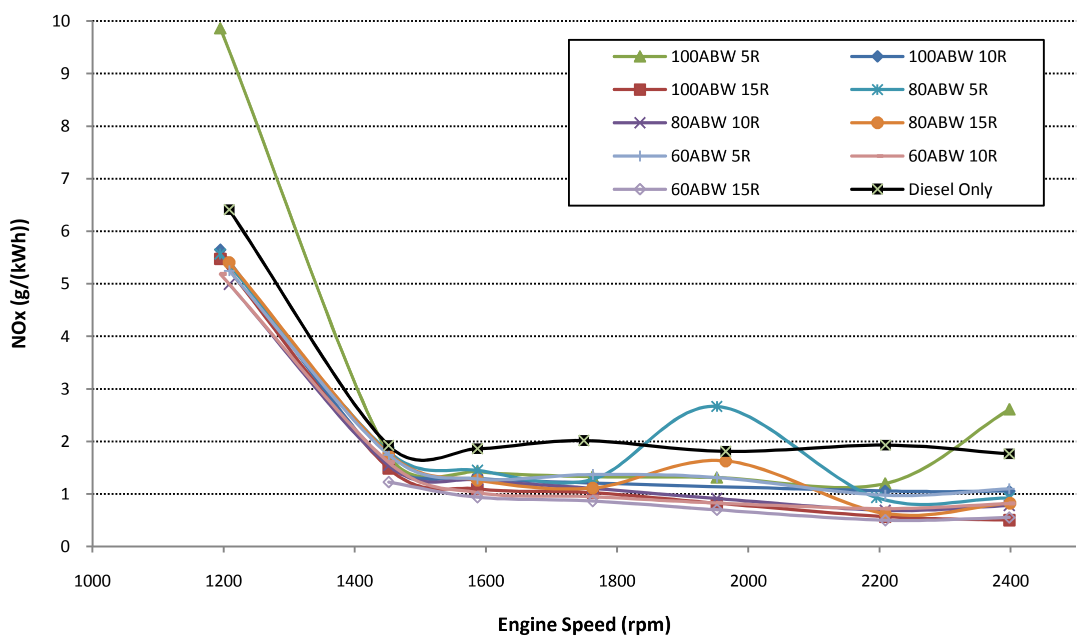

Figure 14. Brake specific NOx emission results (g/kWh) at 50% engine load.

4.1.2 Carbon Monoxide

Carbon monoxide (CO) results showed a statistically significant increase compared to diesel-only when replacement ratio was reviewed (p-value <0.0001). These results coincided with researchers like Walker (1984) and Jiang (1990). CO increased as ethanol replacement rate increased, shown in Figure 15.

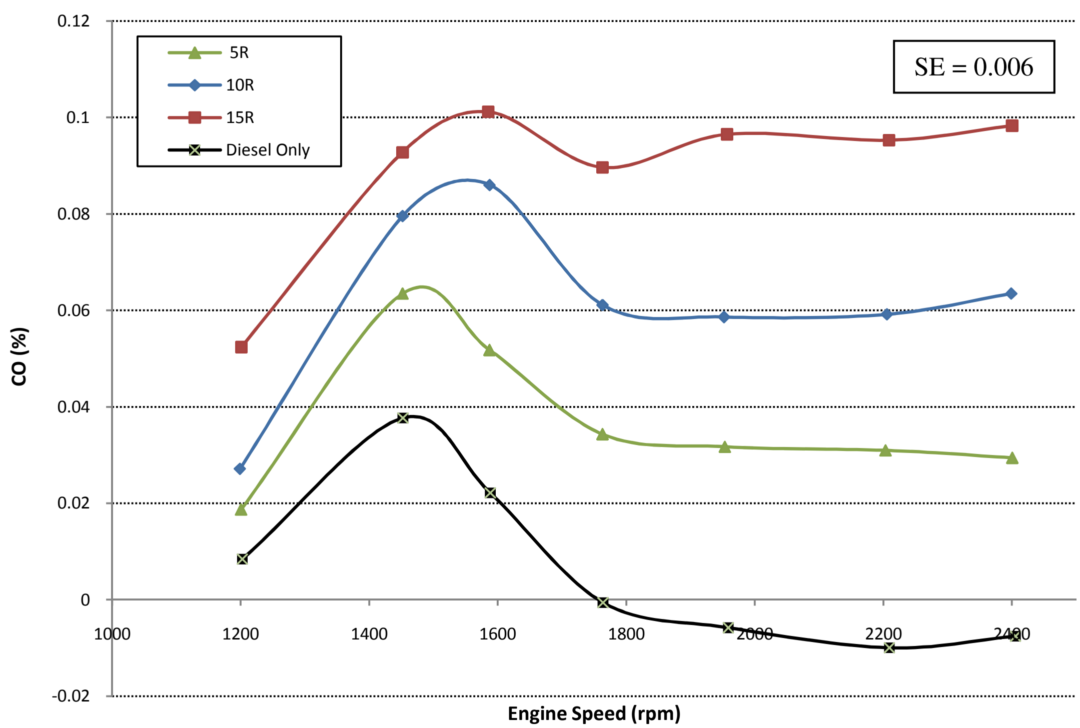

Figure 15. Carbon monoxide emissions, averaged over all loads and mixtures.

4.1.3 Carbon Dioxide

Carbon dioxide (CO_2) results showed a decreasing trend with increases in engine speed after peak torque. Numerous interactions were found in the analysis, so a generalization as to whether CO_2 increased or decreased was not possible. It was found that CO_2 was independent of load, so a plot is shown in Figure 16 with all loads averaged. Note that both diesel-only baselines are plotted individually because statistically they were significantly different. The reason may have been the lack of precision of the CO_2 sensor on the Bridge 5 gas analyzer.

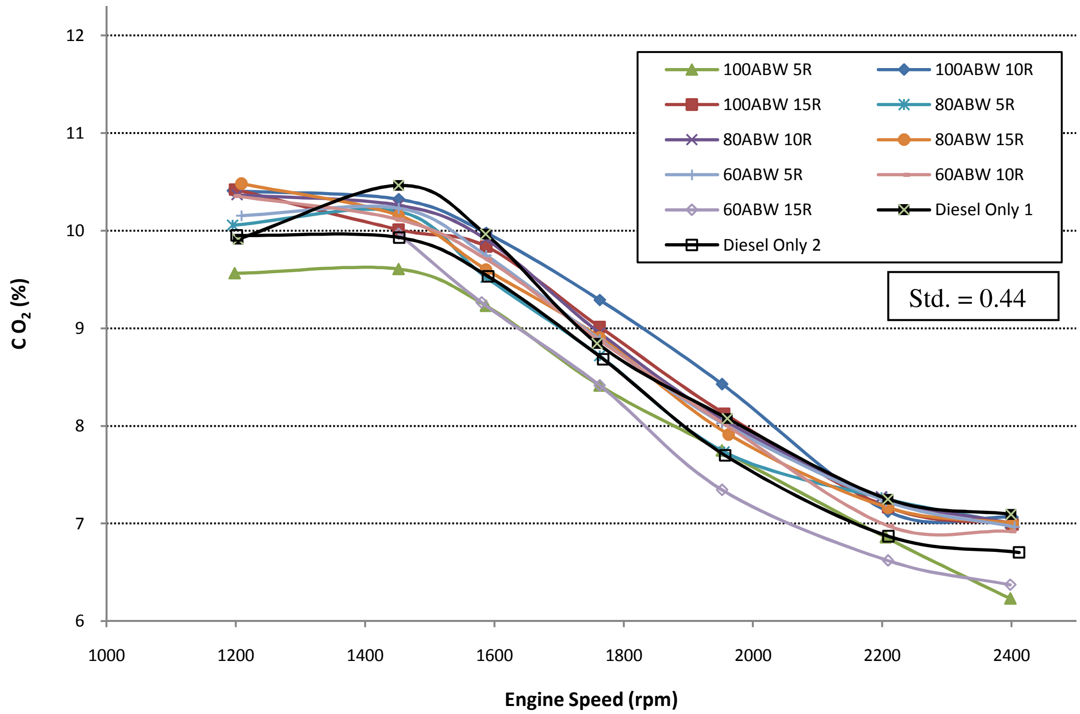

Figure 16. CO_2 results, averaged over all loads.

4.1.4 Oxygen

Oxygen (O_2) results showed an increasing trend with an increase in engine speed. Numerous interactions were found in the analysis, similar to CO_2, so no generalizations could be concluded. It was found that O_2 was independent of load, so an average for all loads plot is shown in Figure 17.

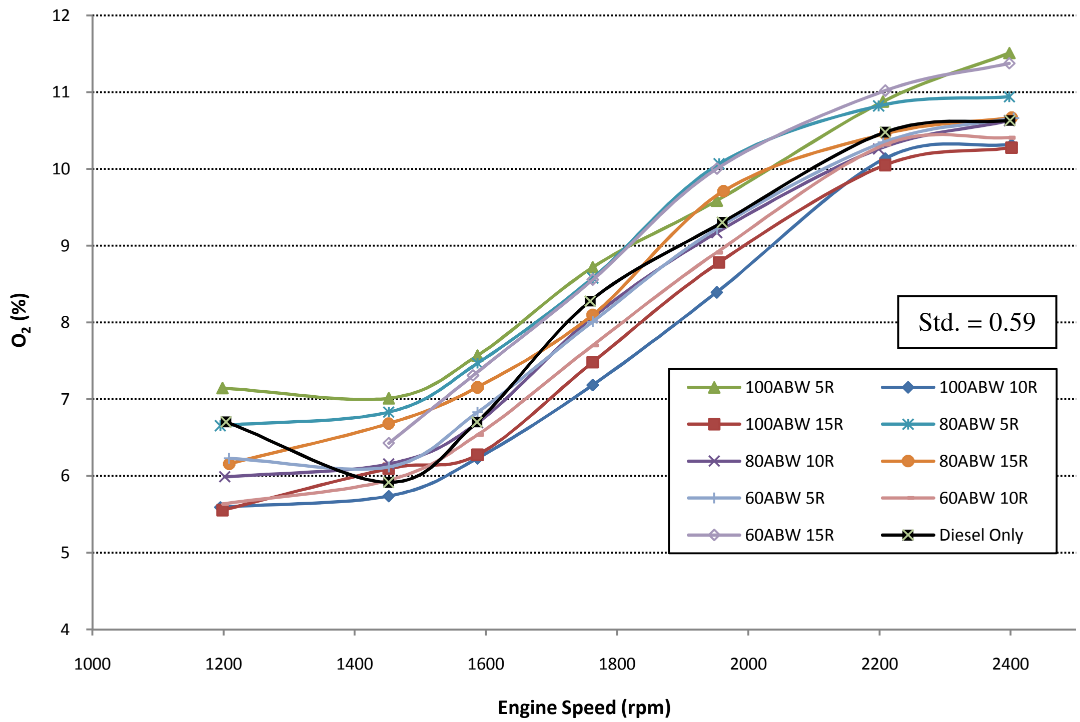

Figure 17. O_2 emission results, averaged over all loads.

4.1.5 Hydrocarbons

Hydrocarbons showed a significant increase for 50, 75, and 90% loads with ethanol fumigation compared to diesel only. The 100% load yielded inconclusive results. Since a load by treatment interaction was found significant (p-value 0.0008), all four loads are shown in Figure 18 through 21.

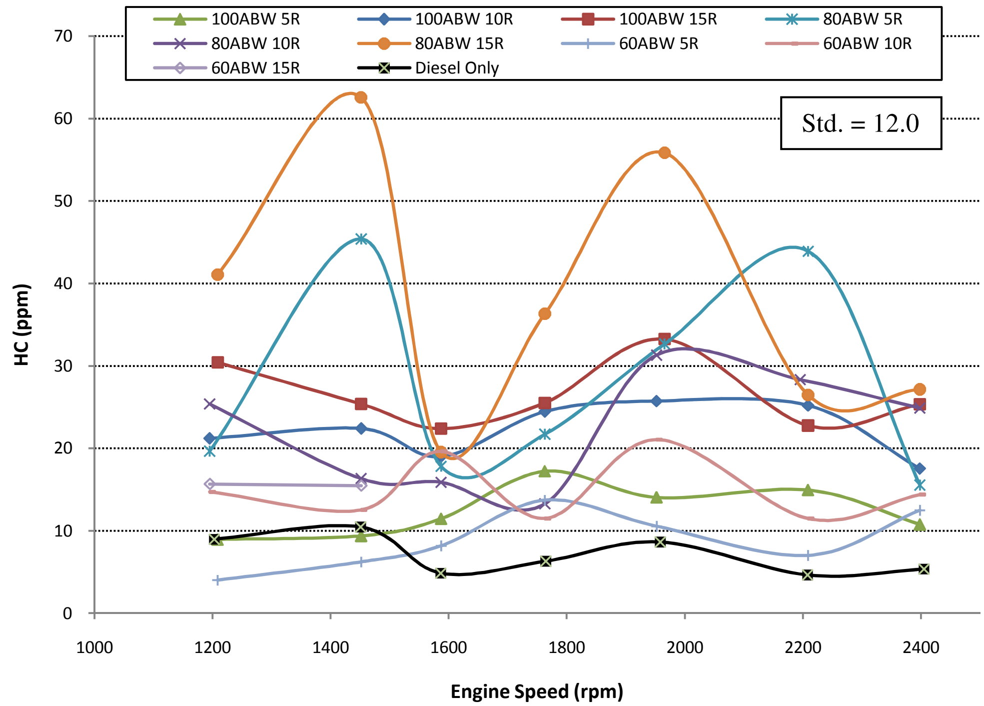

Figure 18. Hydrocarbon emission results (ppm) at 100% engine load.

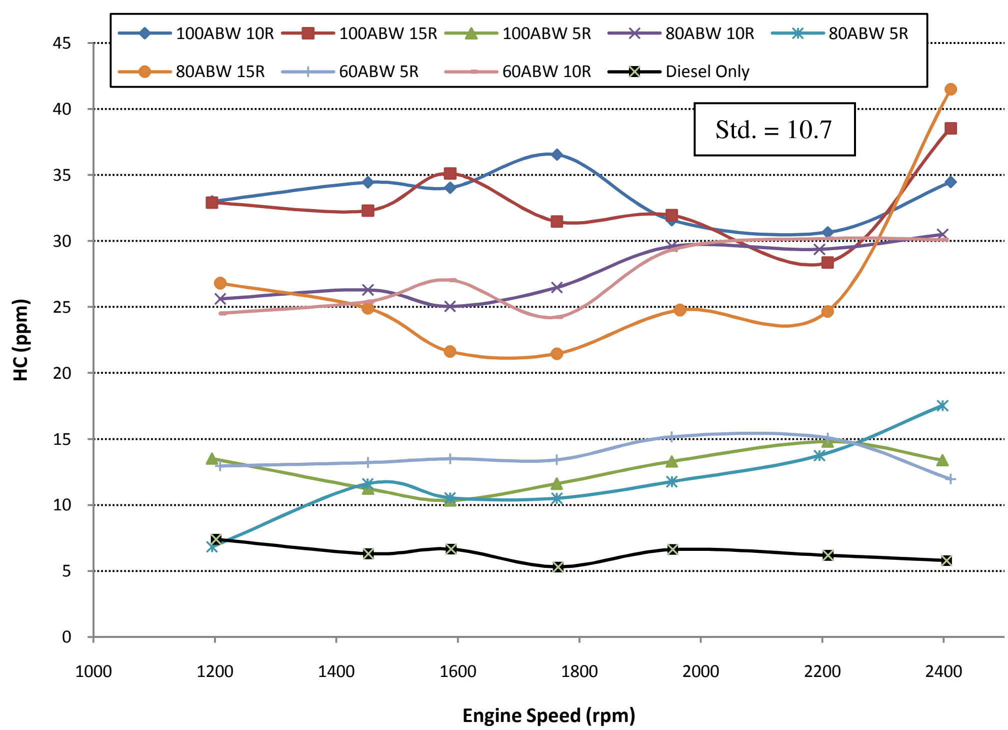

Figure 19. Hydrocarbon emission results (ppm) at 90% engine load.

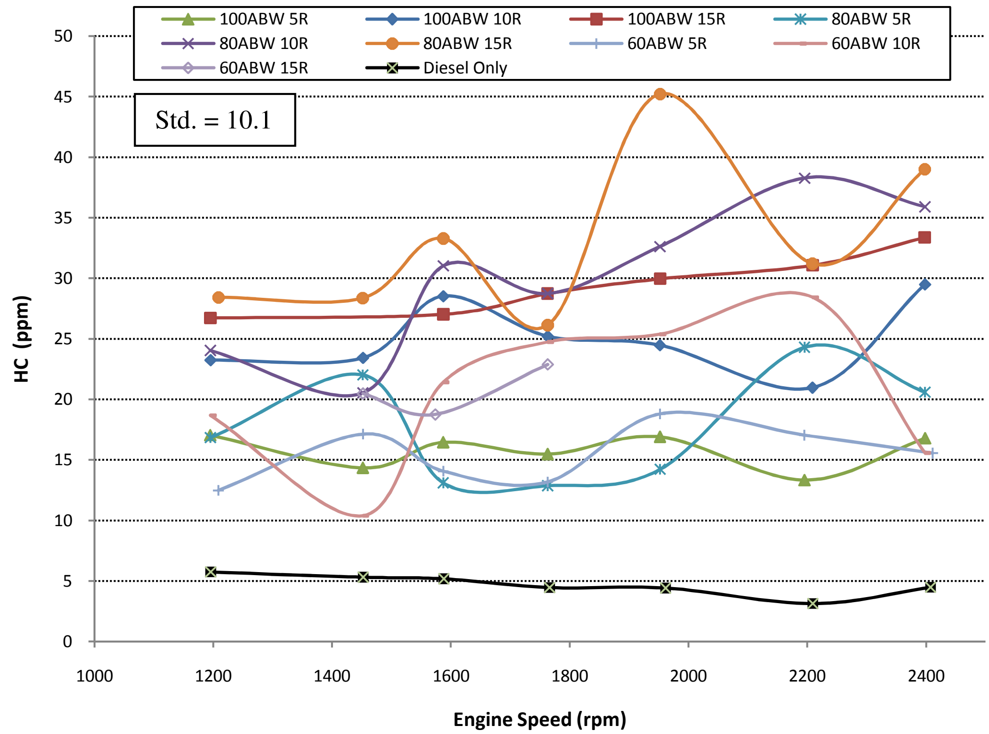

Figure 20. Hydrocarbon emission results (ppm) at 75% engine load.

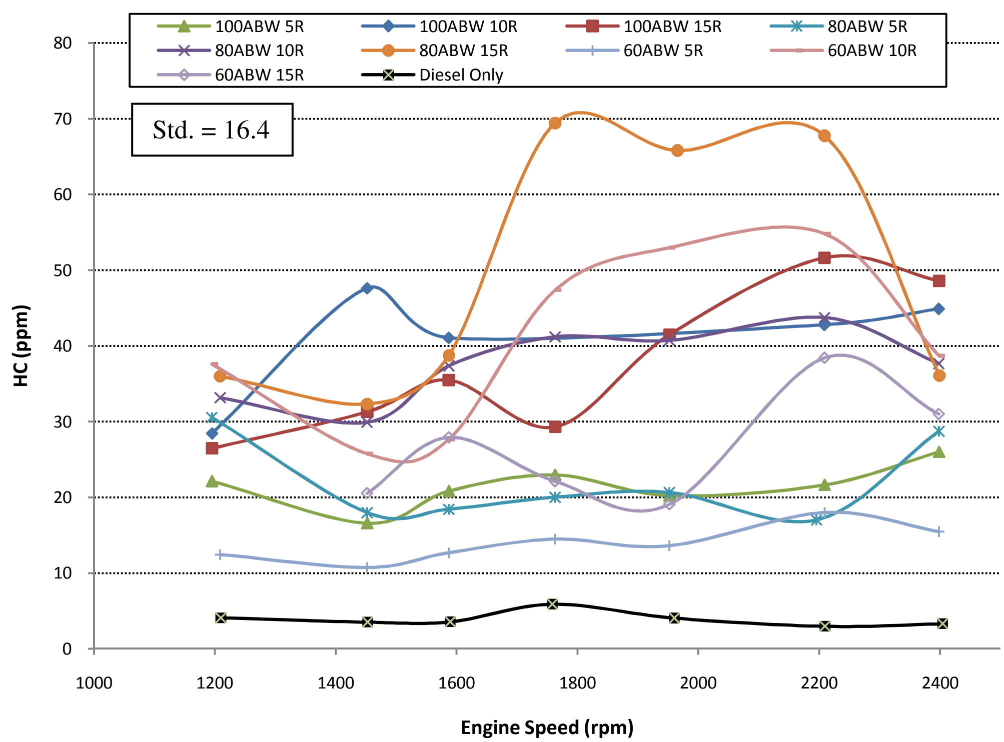

Figure 21. Hydrocarbon emission results (ppm) at 50% engine load.

4.2 Thermal Efficiency Results

Brake thermal efficiency was calculated by dividing useful brake power by total power supplied by the fuel (Goering and Hansen 2004). No significant change in thermal efficiency was observed (p-value 0.8772). By maintaining the diesel only thermal efficiency, there was no energy penalty for using any of the studied ethanol mixtures. The thermal efficiencies for 100% engine load are plotted in Figure 22 as an example.

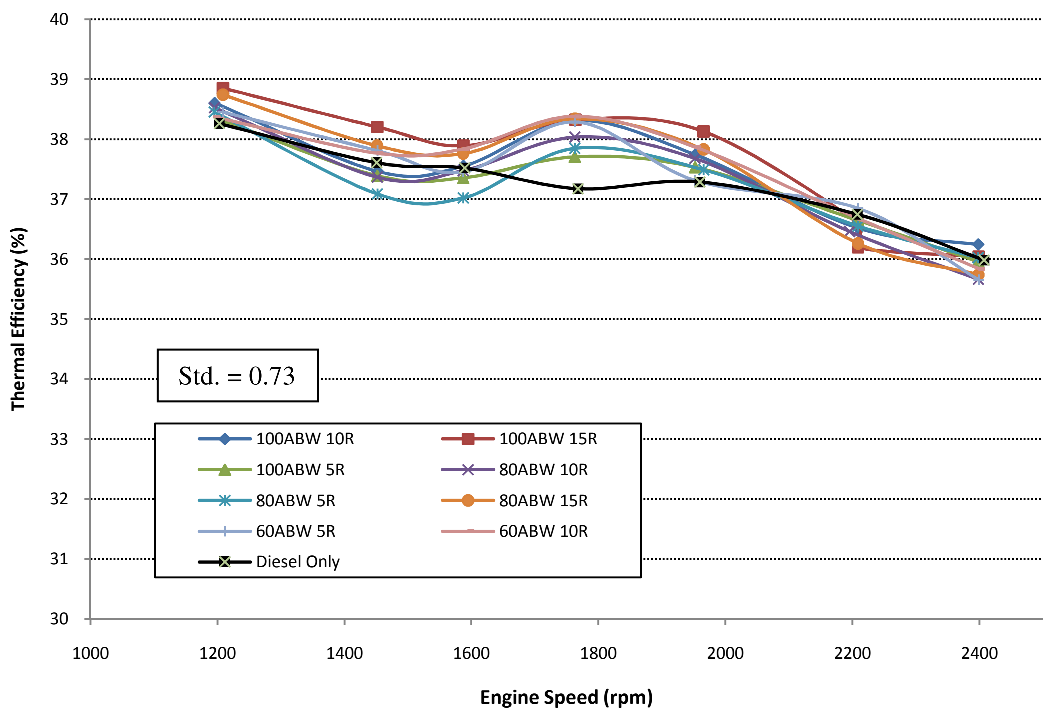

Figure 22. Engine thermal efficiency at 100% engine load.

4.3 Engine Performance Results

During ethanol fumigation tests, no audible change in engine noise occurred, indicating little to no engine knock.

4.3.1 Engine Power and Torque

No differences of power or torque in baseline tests were found. All baseline results were averaged and descriptive engine characteristics were plotted. Engine power plotted versus engine speed is shown in Figure 23. Engine torque plotted versus engine speed is shown in Figure 24. Engine torque (Nm) plotted vs. speed.

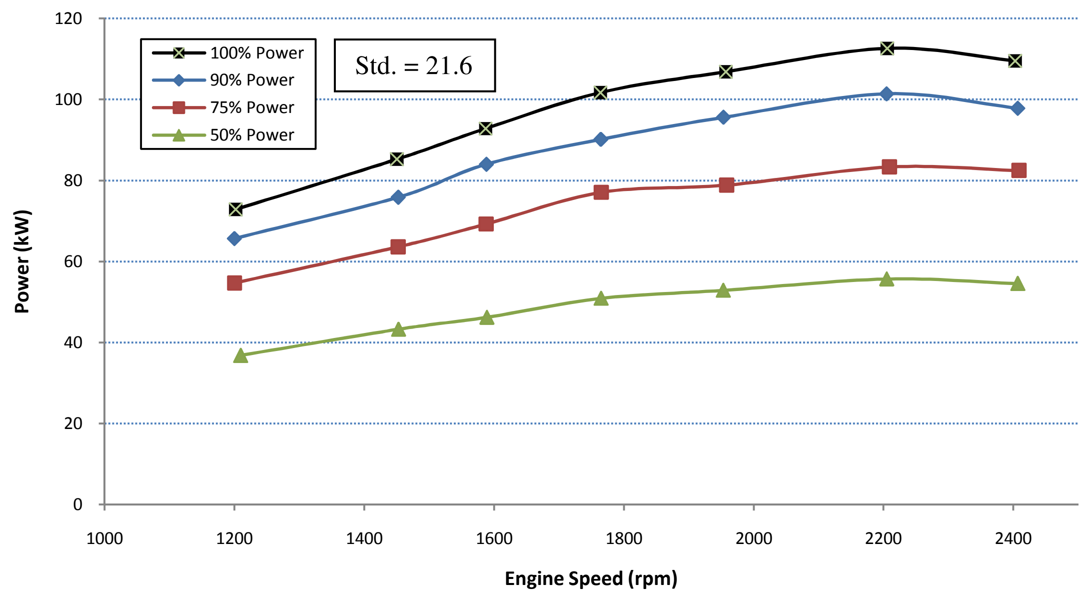

Figure 23. Engine power (kW) plotted vs. speed.

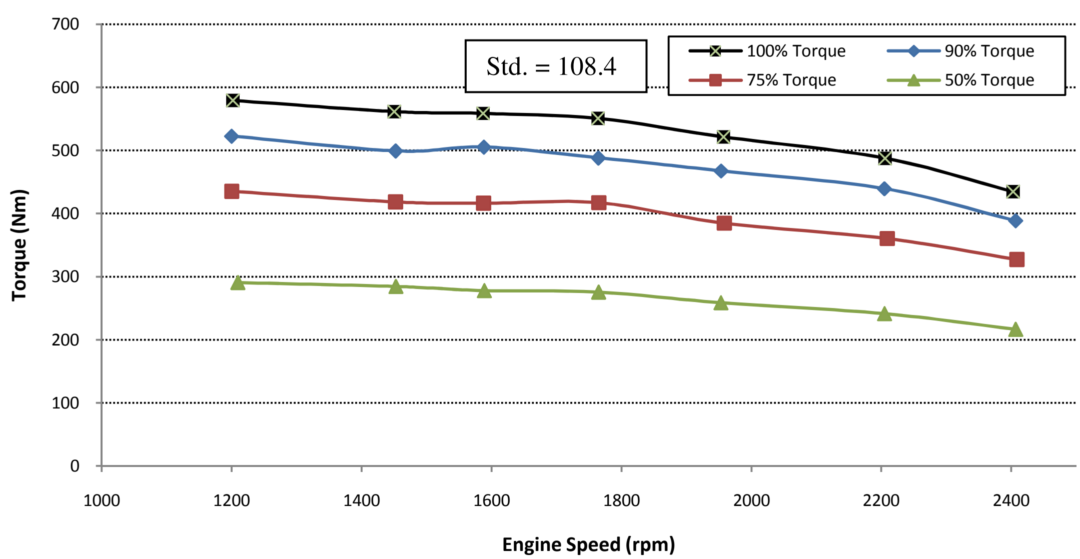

Figure 24. Engine torque (Nm) plotted vs. speed.

4.3.2 Brake Specific Fuel Consumption

Brake specific fuel consumption (BSFC) is shown in Figure 25.

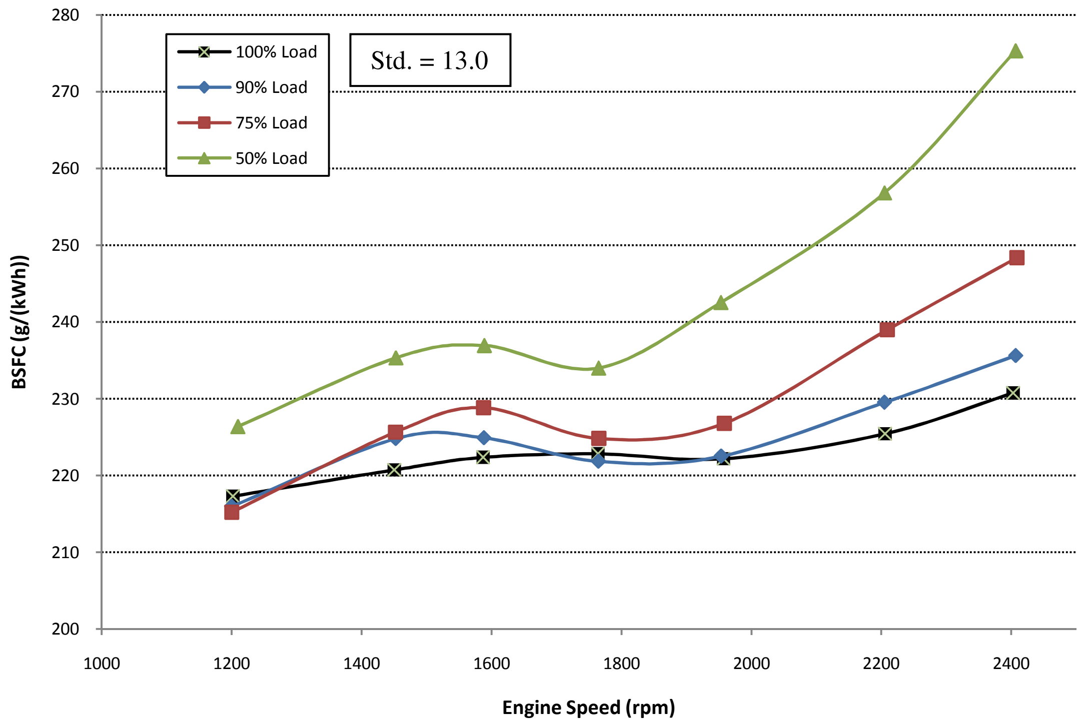

Figure 25. Engine brake specific fuel consumption for four engine loads.

4.3.3 Turbocharger

Turbocharger compressor blade wear was monitored visually. Photos, taken before and after each test, indicated no visible wear. A gold discoloration was found on the turbocharger casting after ethanol fumigation, most noticeably after 100ABW. No visual pitting of the compressor blade tips was found. This does not coincide with the Sullivan and Bashford research (Sullivan and Bashford 1981). Very light scuffing was shown on compressor blades prior to testing from previous fumigation work. A photo of the compressor blades when the engine was new is shown in Figure 26. Photos of the compressor blades before and after this research are shown in Figure 27. The blue mark on one blade is from a paint pen in an attempt to monitor wear. The lack of compressor blade wear may be explained by the compressor blade material, by the fine atomization of fumigated ethanol and water and/or by the relatively small time of the experiments. It seems that liquid can be fumigated in advance of the compressor without damage if sufficient atomization is achieved.

Figure 26. Compressor before any fumigation

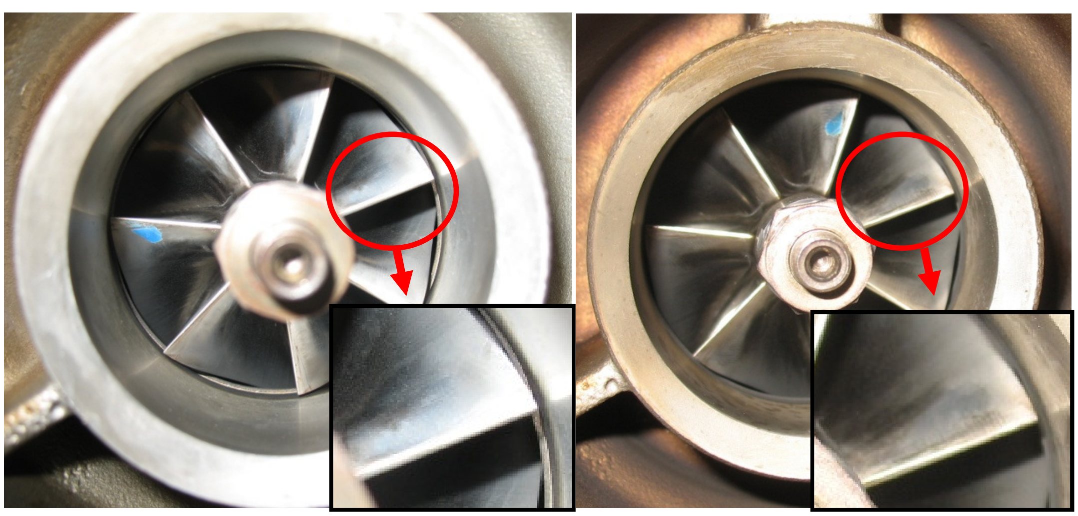

Figure 27. Photos of Turbocharger before (left) and after (right) ethanol fumigation study

Fumigation occurred before the turbocharger and intercooler. There was concern that the fumigated mixture would condense in the bottom of the intercooler. This was monitored visually directly at the end of engine testing by removing the rubber boot between the turbocharger tube and intercooler. No indication of condensation was found.

4.4 Future Work

The engine had a total run time of 67.3 h with fumigation in advance of the turbocharger for this study. Engine and turbocharger durability need to be studied. A study to continue this research should include instrumentation of the cylinder head for cylinder temperatures and pressures, and individual exhaust port temperatures to monitor whether uniform cylinder to cylinder distribution occurs.

5 Water Fumigation Results

During the water fumigation study, the average relative humidity (RH) was approximately 18%.

5.1 Emissions Results

As with ethanol, a reduction of NOx emissions was found as water fumigation flow rate increased. Modeling the response of NOx showed that the slope with respect to the percentage of water was significant (p-value <0.0001). Fumigation of water was limited to 24% of the diesel flow rate because of the limitation of the nozzle. The NOx results are shown in Figure 28.

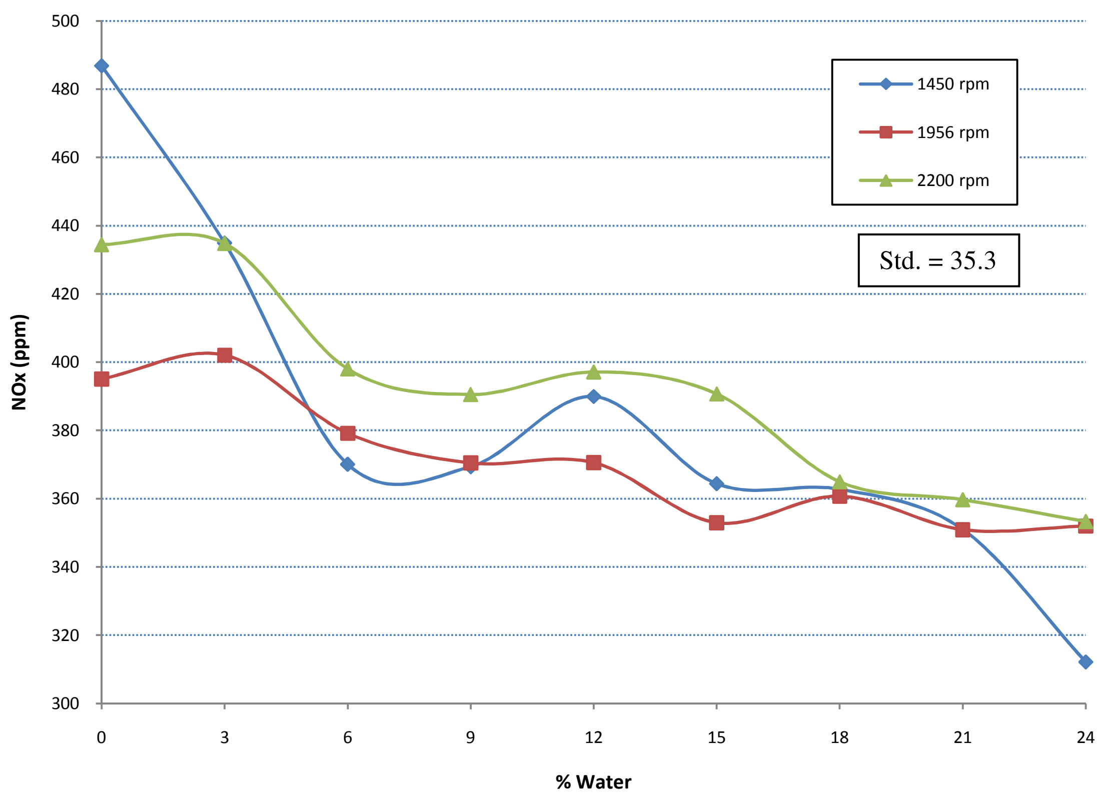

Figure 28. NOx at 100% engine load with water fumigation

CO emissions slightly increased compared to diesel-only but showed no trends with increasing water fumigation. No change in HC, CO_2, or O_2 emissions by water fumigation occurred.

5.2 Thermal Efficiency Results

No significant change in thermal efficiency (p-value 0.7336) was found by introducing water in advance of the turbocharger. A plot of thermal efficiency is shown in Figure 29.

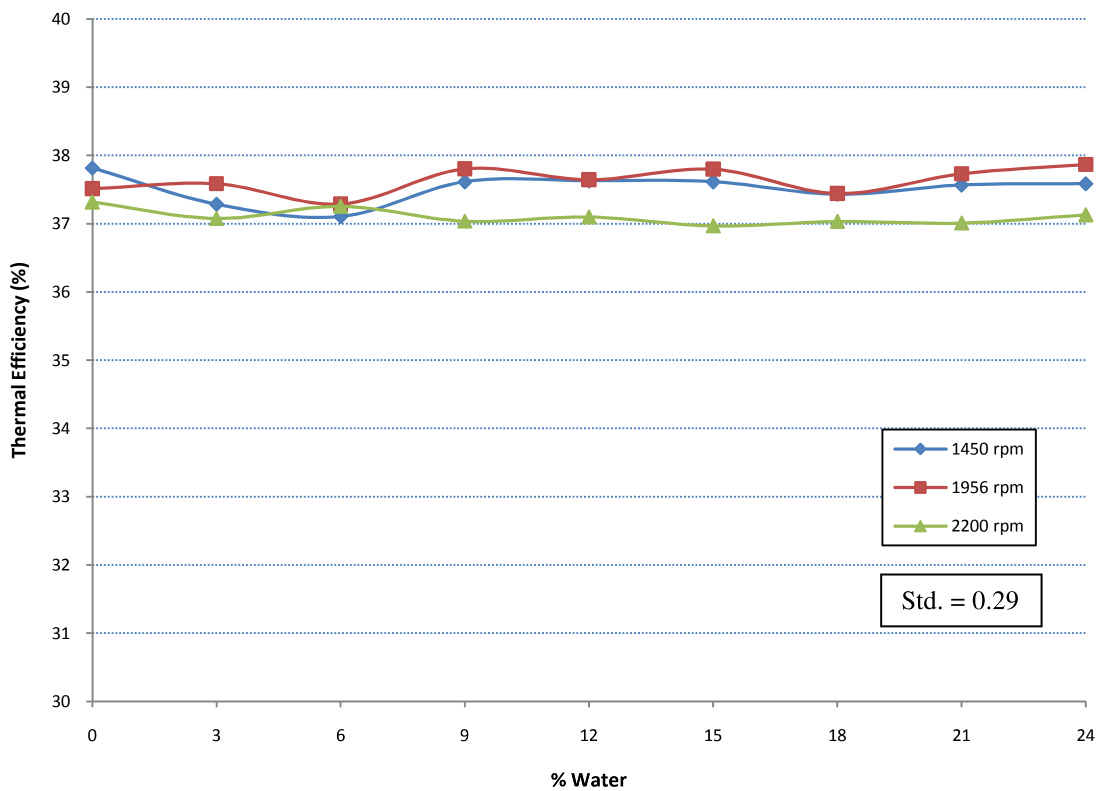

Figure 29. Thermal efficiency at 100% load with water fumigation.

5.3 Engine Performance Results

No change in engine power occurred when fumigating water, (p-value 0.7951). The average engine powers at 1450, 1956 and 2200 rpm were 85.2, 107.3 and 113.3 kW, respectively.

5.4 Future Work

Quick calculations of the amount of water that was fumigated showed that the relative humidity in the intake increased to 70-80% RH from 18% RH when fumigation with 24% of the diesel fuel rate. Since the fumigation of water did not exceed the air saturation point, a study to review 100% relative humidity or higher would be in order.

6 Conclusions

Thermal efficiency was not compromised when both ethanol and water fumigation were implemented. Both types of fumigation were shown to significantly decrease NOx emissions. Ethanol fumigation was more effective than water-only fumigation to decrease NOx. NOx reduction was found to be dependent on the energy replacement rate of the diesel instead of the mixtures that were examined. The emissions of CO and HC increased with ethanol fumigation, while changes in CO_2 and O_2 emissions were not found significant. No significant changes in HC, CO_2, or O_2 were found with water fumigation, but CO increased slightly when compared to the diesel baseline.

The turbocharger compressor was monitored visually before and after testing. No visual wear was observed. The lack of compressor blade wear may be explained by the compressor blade material, by the fine atomization of fumigated ethanol and water and/or by the relatively short engine experiment.

Limitations to the study existed. Only one engine was tested while EPA emission tests normally use more engines to insure that the conclusions reached are applicable to the full population of each engine model. The test data reflected steady state data at each engine speed, while EPA emissions tests are conducted in transient engine operating conditions. The emissions analyzer was not of sufficient resolution to perform EPA certified tests but did allow the emissions results to be recorded on a ppm and percentage basis for analysis of trends.

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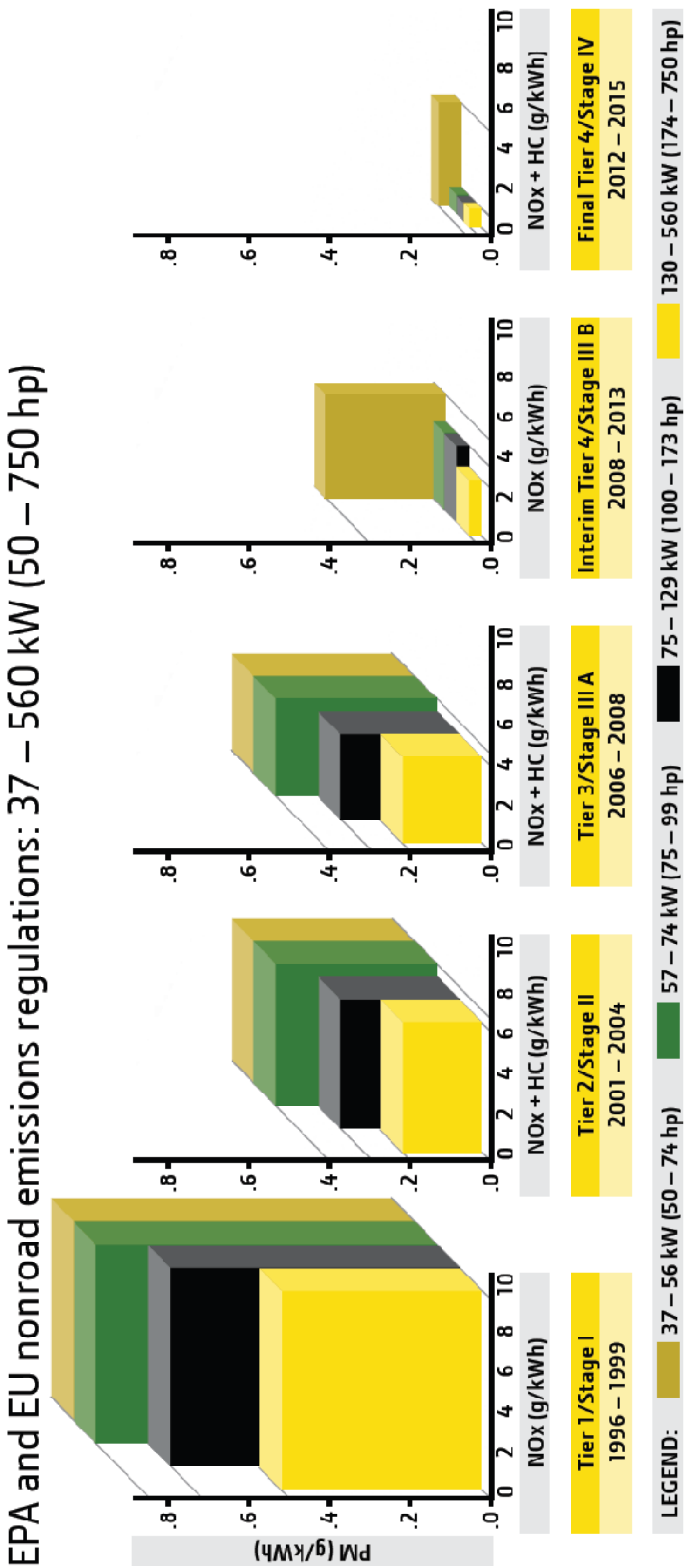
Appendix A

Emission Regulation Trends

(Deere & Co. 2009)



Appendix B

Engine Break-In Procedure

Engine Speed (rpm)	Engine Load (%)	Duration (minutes)
2000	70	5
2000	80	5
2000	60	5
1400	60	5
1400	80	5
1400	70	5
2200	80	5
2200	70	5
2200	60	5
2400	80	5
2400	60	5
2400	70	5
1600	60	5
1600	70	5
1600	80	5
1800	70	5
1800	60	5
1800	80	5

* Repeated until 20 engine hours were reached.

Appendix C

Test Schedule

Test	Date	Engine Hours at Start of Test
60ABW 0R	2/3/2010	81.5
60ABW 5R	2/11/2010	85.5
60ABW 15R	2/11/2010	91.3
60ABW 10R	2/12/2010	94.1
100ABW 15R	2/16/2010	98.8
100ABW 0R	2/17/2010	103.1
100ABW 10R	2/17/2010	106.9
100ABW 5R	2/18/2010	112.4
80ABW 5R	2/22/2010	117.9
80ABW 15R	2/23/2010	122.7
80ABW 10R -1	2/24/2010	127.9
80ABW 10R-2	3/5/2010	130.2
80ABW 0R	3/5/2010	132.5
80ABW 0R	3/6/2010	135.8
60ABW 5R	3/6/2010	No record
60ABW 15R	3/6/2010	No record
60ABW 10R	3/6/2010	138.9
100ABW 15R	3/6/2010	140.3
100ABW 10R	3/6/2010	142.1
80ABW 10R	3/7/2010	143.2
Water Part 1	3/9/2010	144.7
Water Part 2	3/10/2010	148.8

Appendix D

LabVIEW Data Acquisition Program

Page 1

Producer/Consumer Design Pattern (Data)
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Connector Pane

Producer/Consumer Design Pattern (Data)

Use this template to build a producer/consumer design pattern. Use this template when you need to execute a process, suc data analysis, when a data source, such as a triggered acquisition, produces data at an uneven rate and you need to execut the process when the data becomes available.

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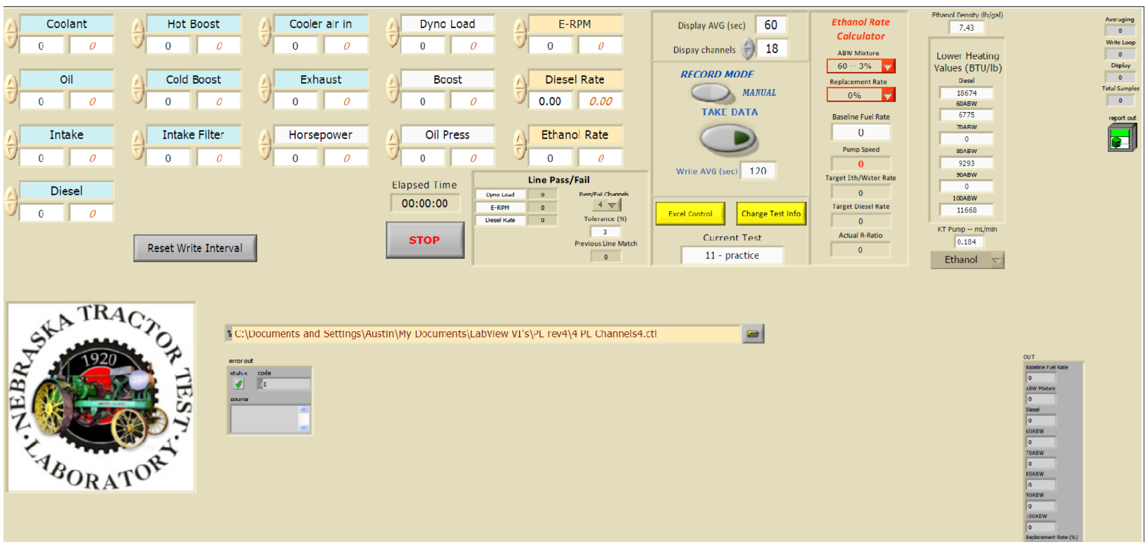

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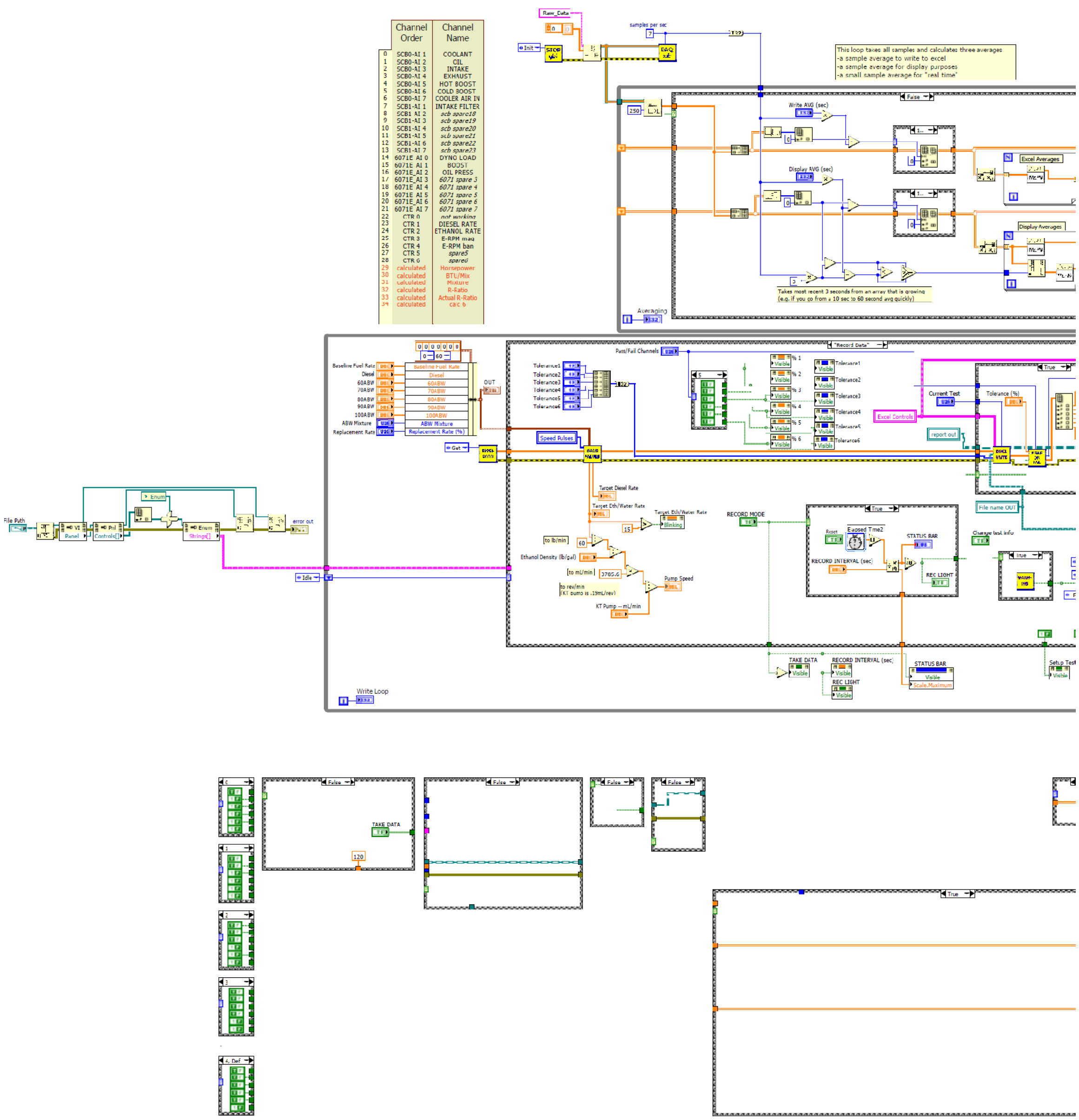

Page 3 NTTL PTO

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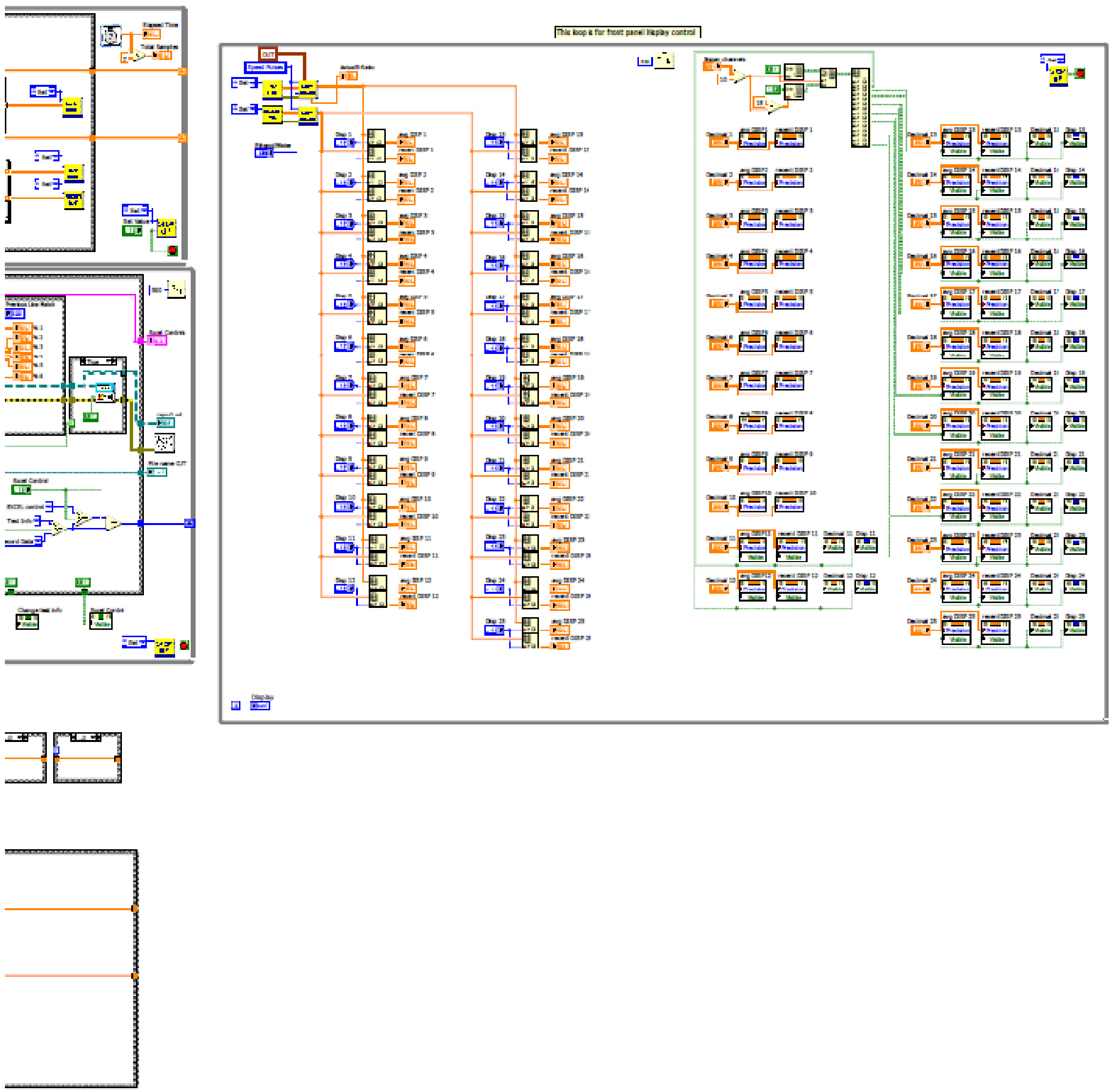

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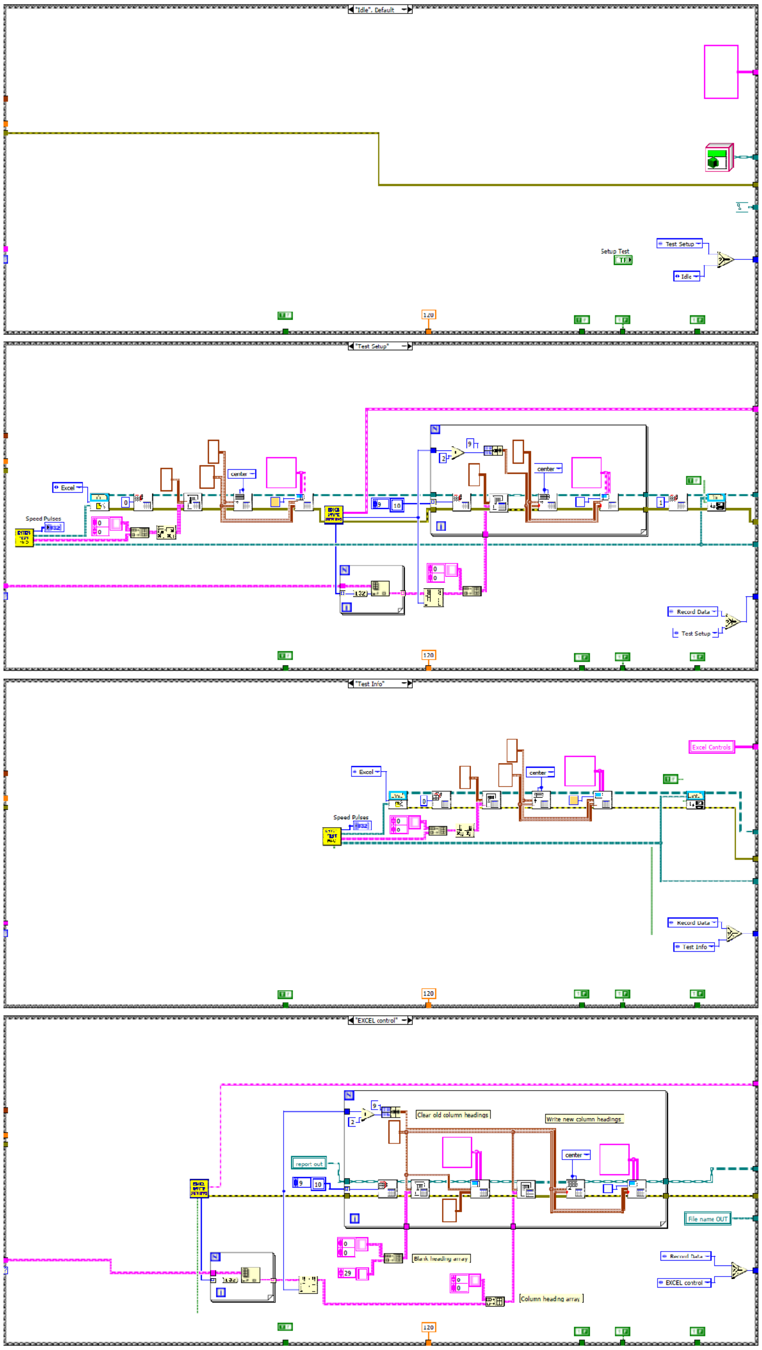

Express VI Configuration Information

Elapsed Time2
Elapsed Time
Indicates the amount of time that has elapsed since the specified start time.

This Express VI is configured as follows:

Time Target: 1 s
Auto Reset: Off

Elapsed Time
Elapsed Time
Indicates the amount of time that has elapsed since the specified start time.

This Express VI is configured as follows:

Time Target: 1 s
Auto Reset: Off

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Connector Pane

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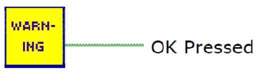

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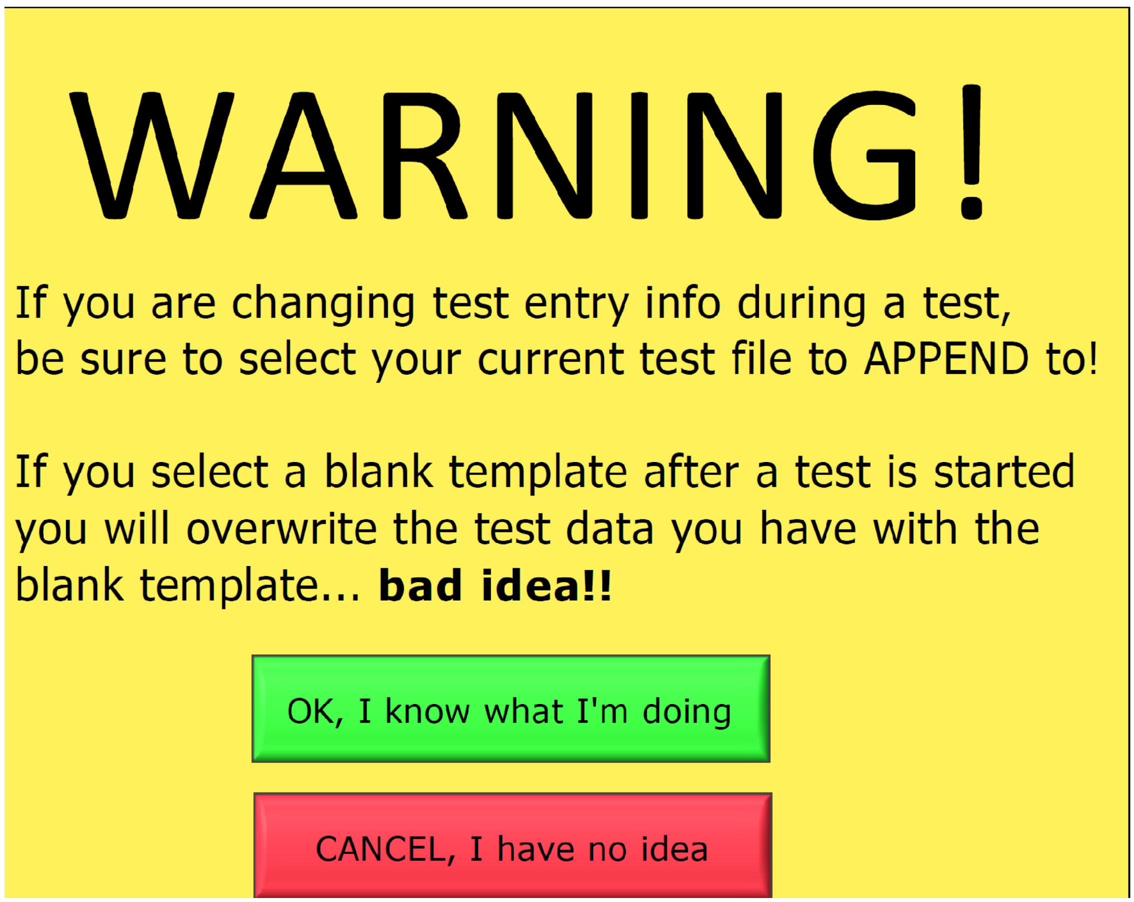

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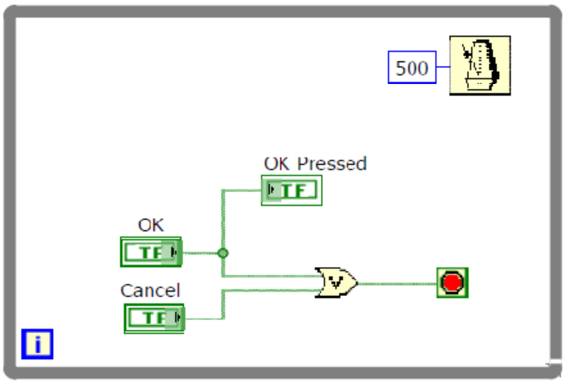

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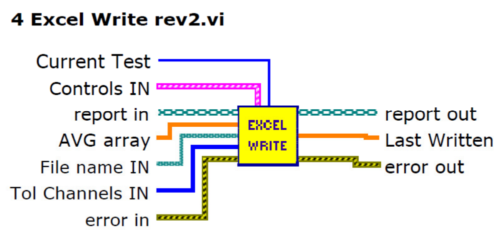

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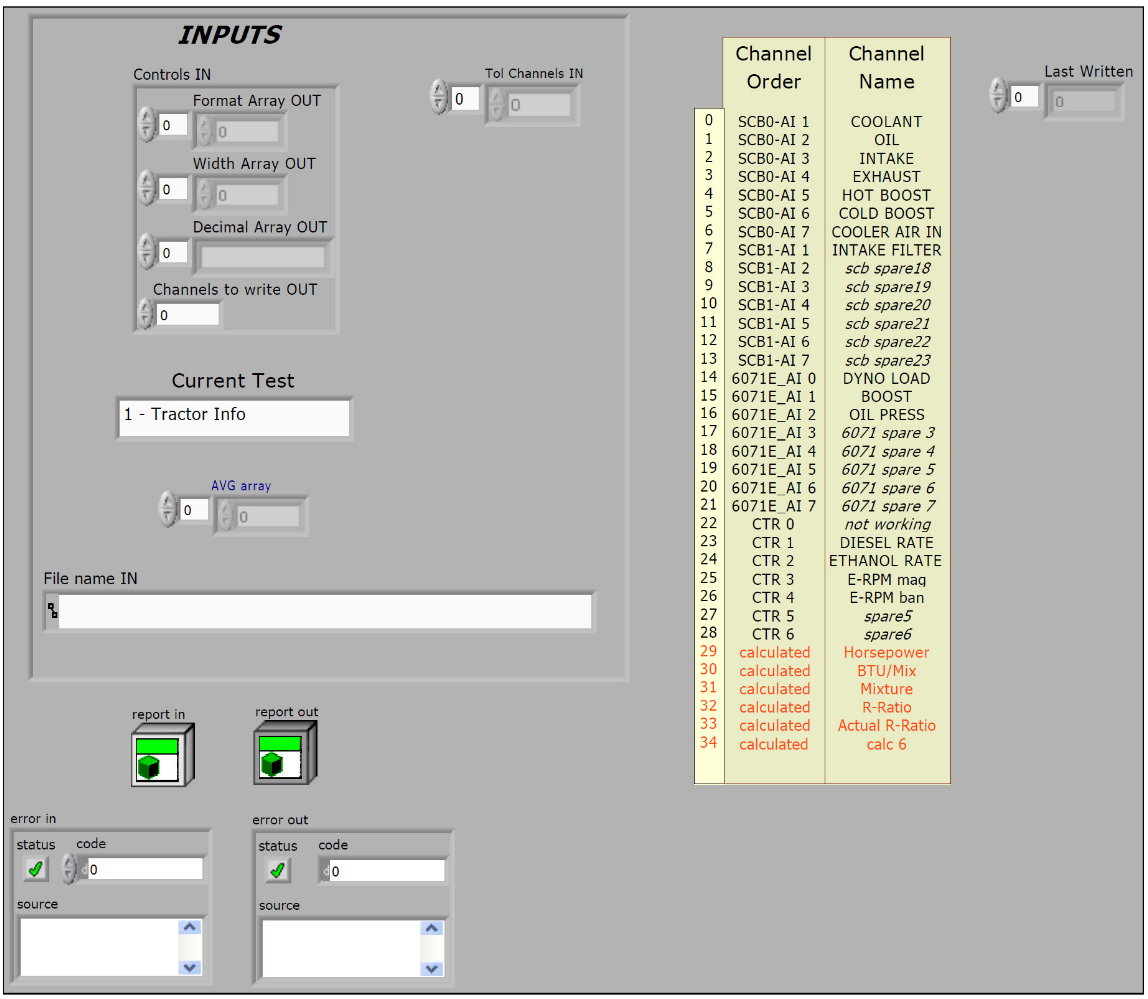
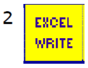


Page 2 

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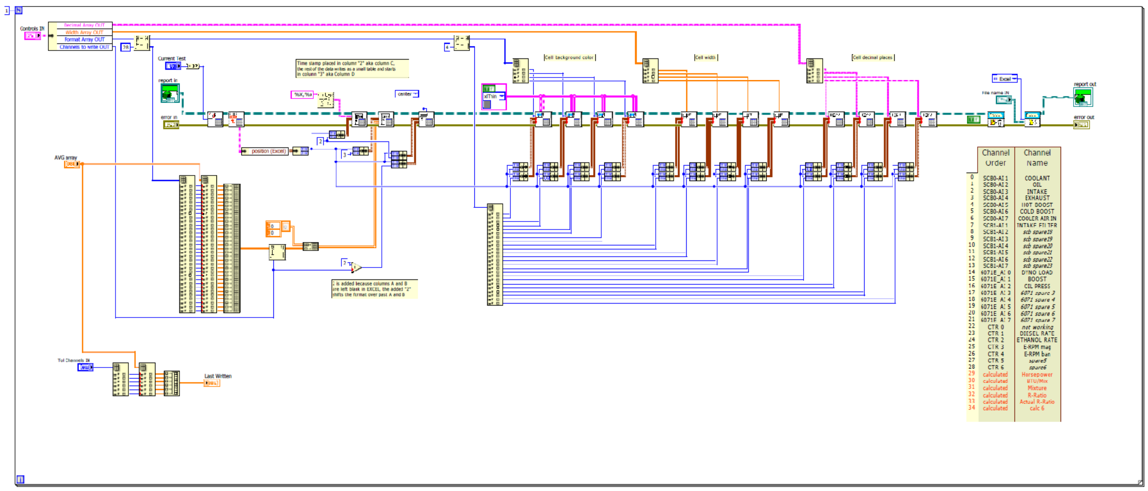
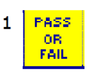


Page 1 

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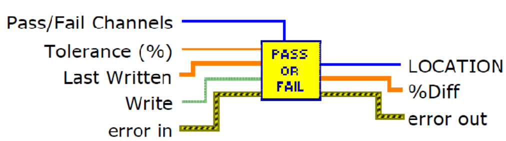

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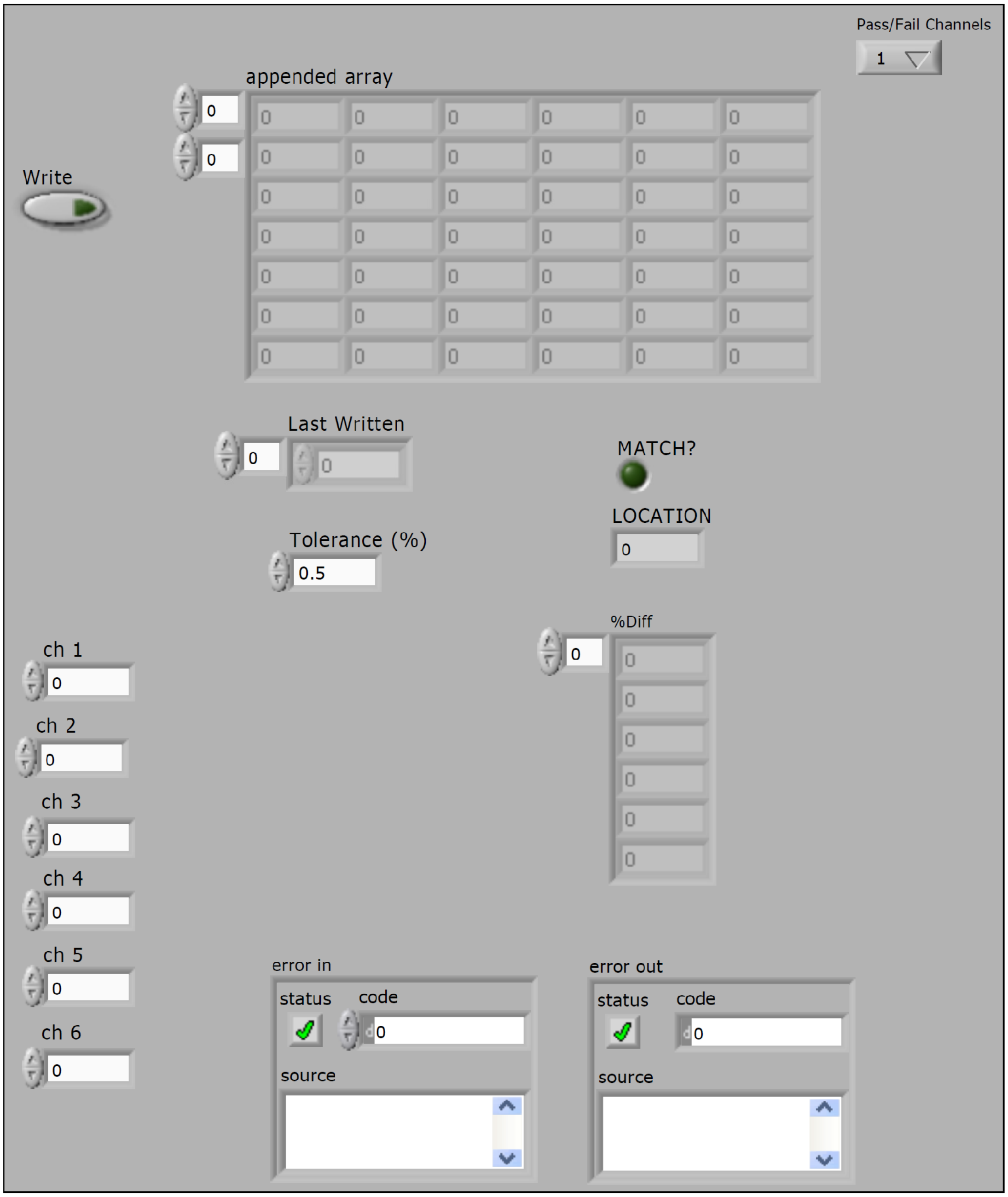

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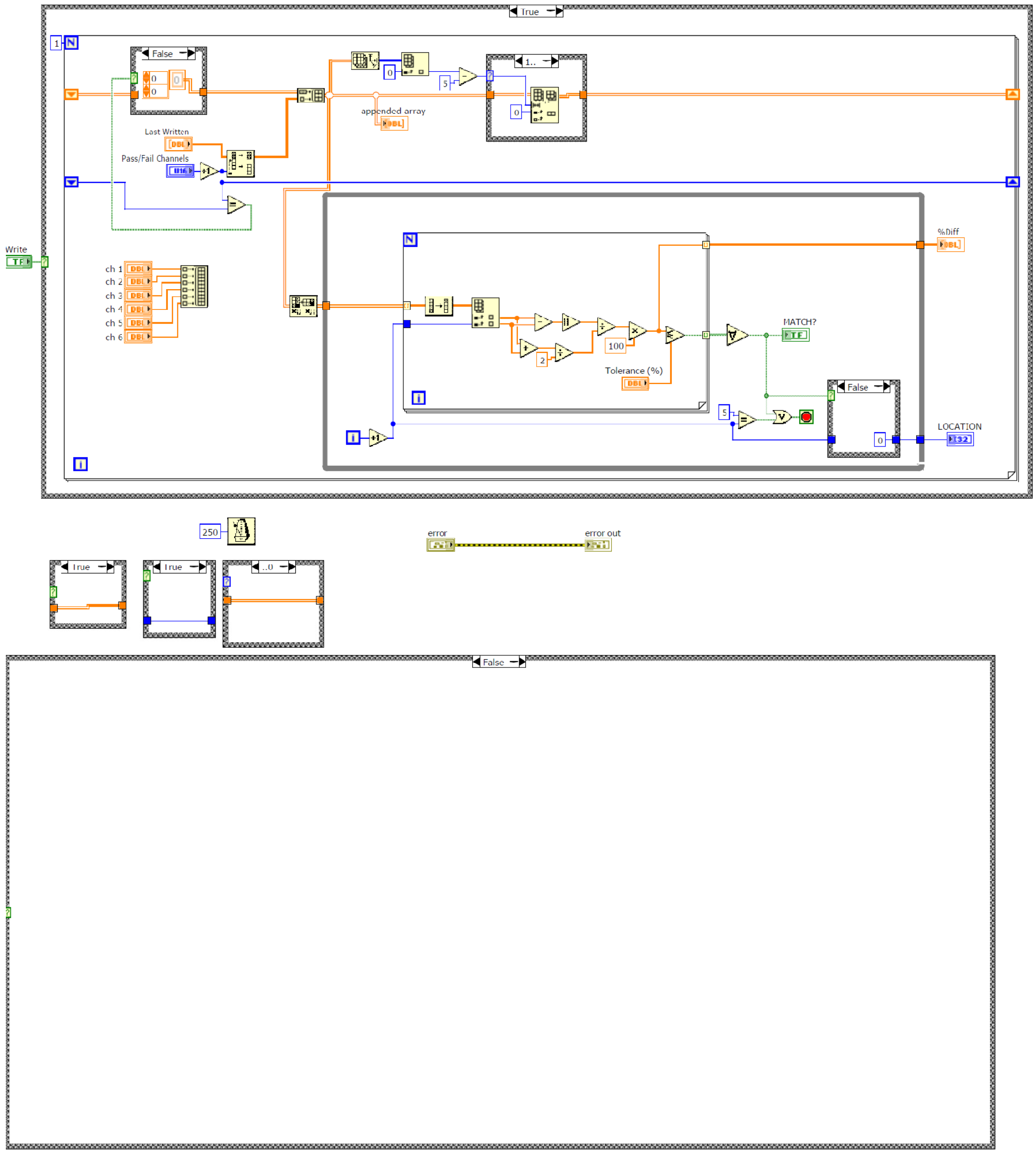

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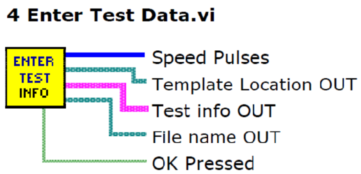

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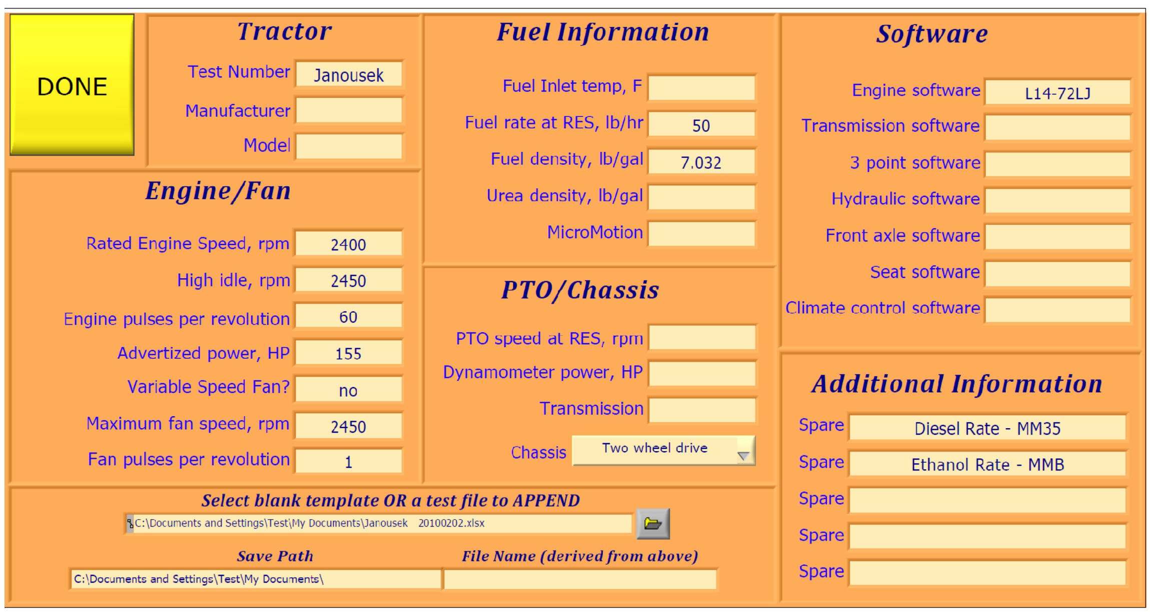

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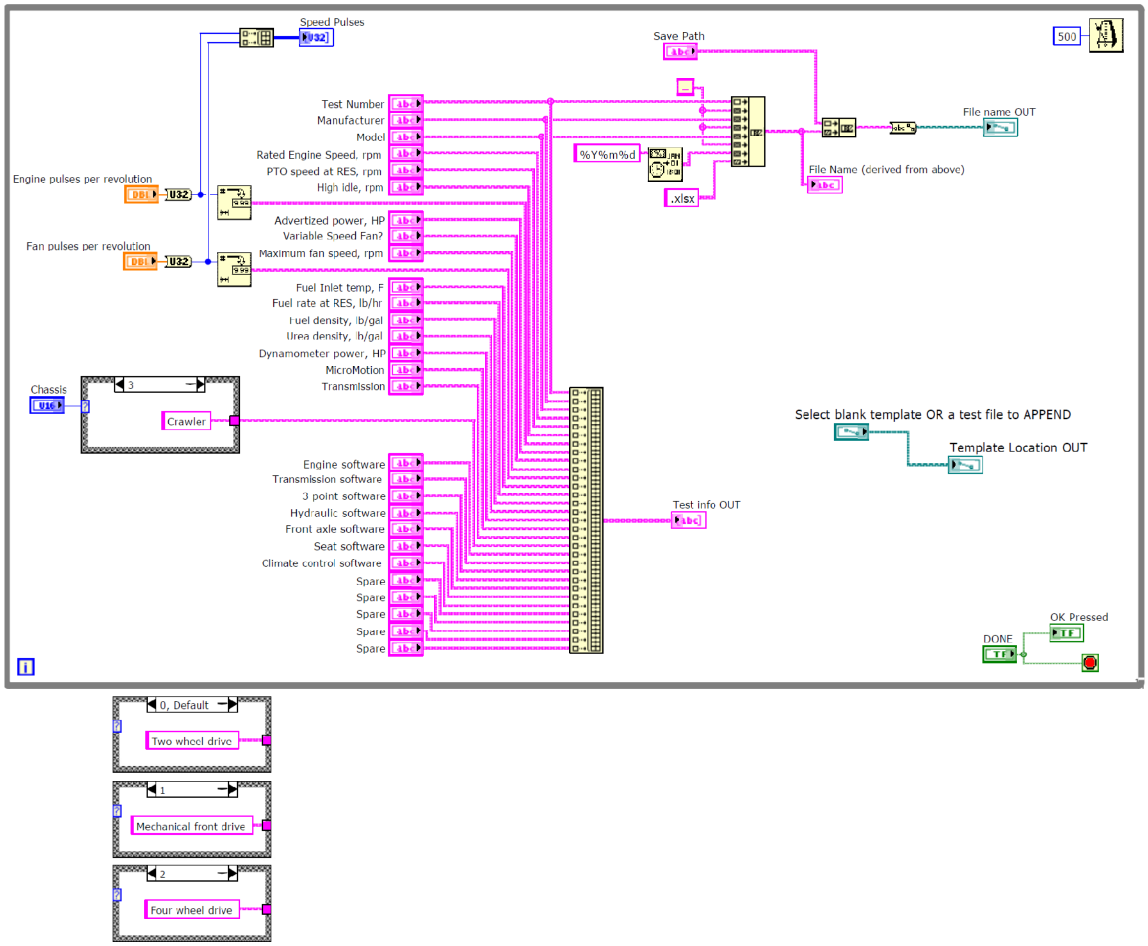

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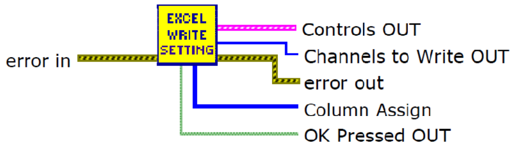

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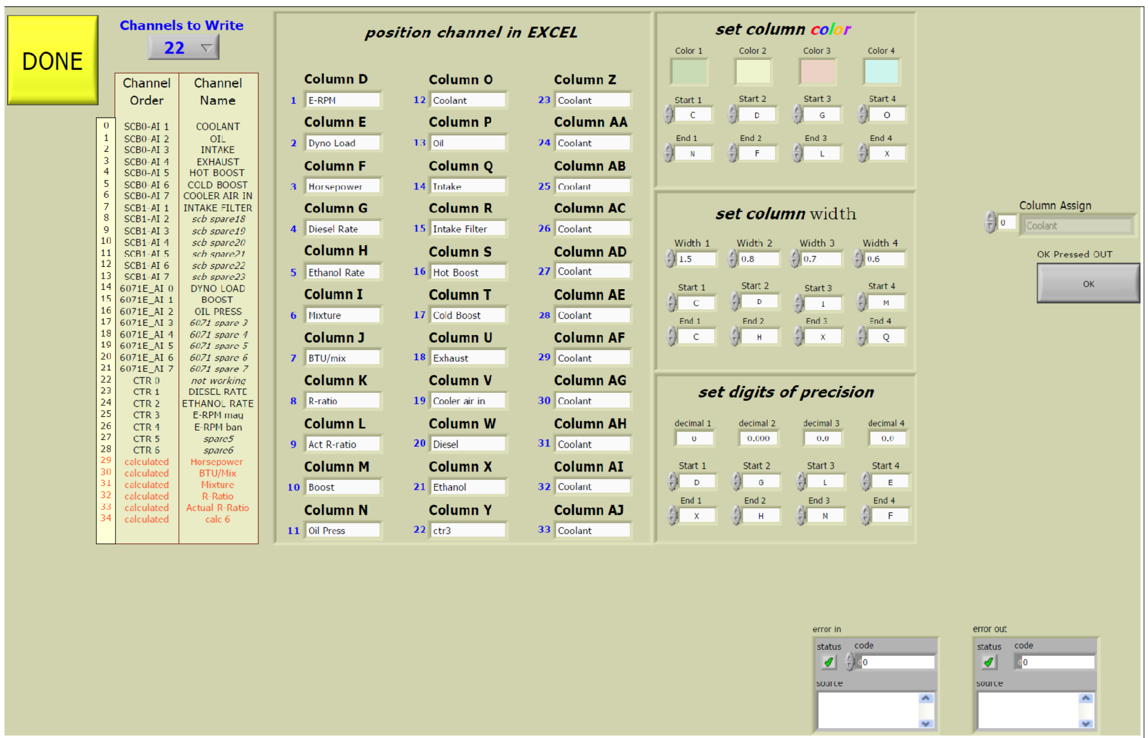

 

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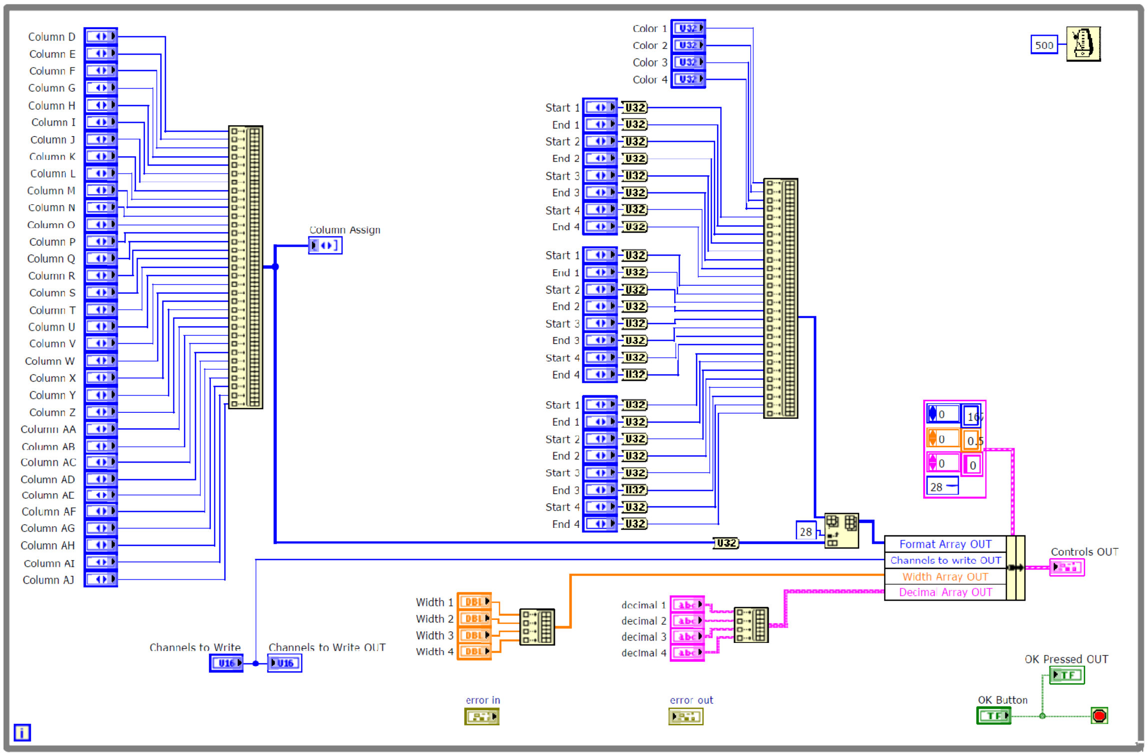

 

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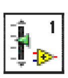

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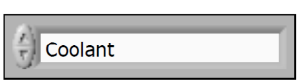
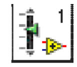


Page 1 

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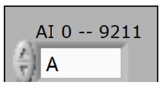

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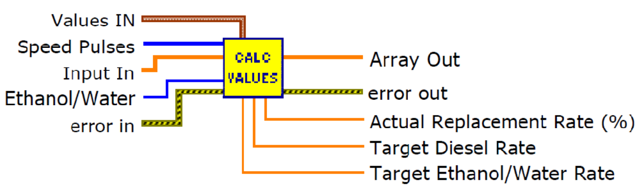

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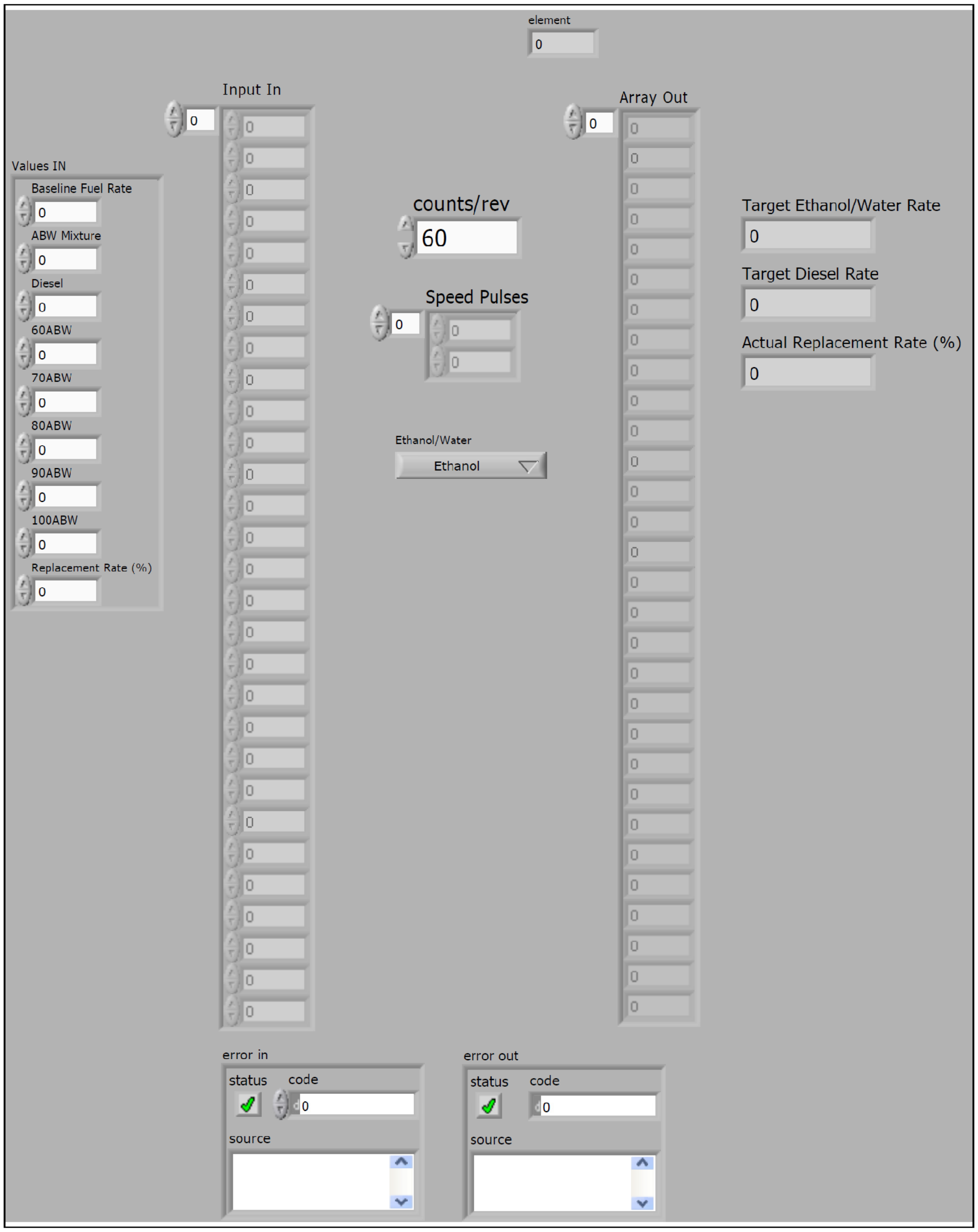

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Block Diagram

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2	SCB0-AI 3	INTAKE
3	SCB0-AI 4	EXHAUST
4	SCB0-AI 5	HOT BOOST
5	SCB0-AI 6	COLD BOOST
6	SCB0-AI 7	COOLER AIR IN
7	SCB1-AI 1	INTAKE FILTER
8	SCB1-AI 2	*scb spare18*
9	SCB1-AI 3	*scb spare19*
10	SCB1-AI 4	*scb spare20*
11	SCB1-AI 5	*scb spare21*
12	SCB1-AI 6	*scb spare22*
13	SCB1-AI 7	*scb spare23*
14	6071E_AI 0	DYNO LOAD
15	6071E_AI 1	BOOST
16	6071E_AI 2	OIL PRESS
17	6071E_AI 3	*6071 spare 3*
18	6071E_AI 4	*6071 spare 4*
19	6071E_AI 5	*6071 spare 5*
20	6071E_AI 6	*6071 spare 6*
21	6071E_AI 7	*6071 spare 7*
22	CTR 0	*not working*
23	CTR 1	DIESEL RATE
24	CTR 2	ETHANOL RATE
25	CTR 3	E-RPM mag
26	CTR 4	E-RPM ban
27	CTR 5	*spare5*
28	CTR 6	*spare6*
29	calculated	Horsepower
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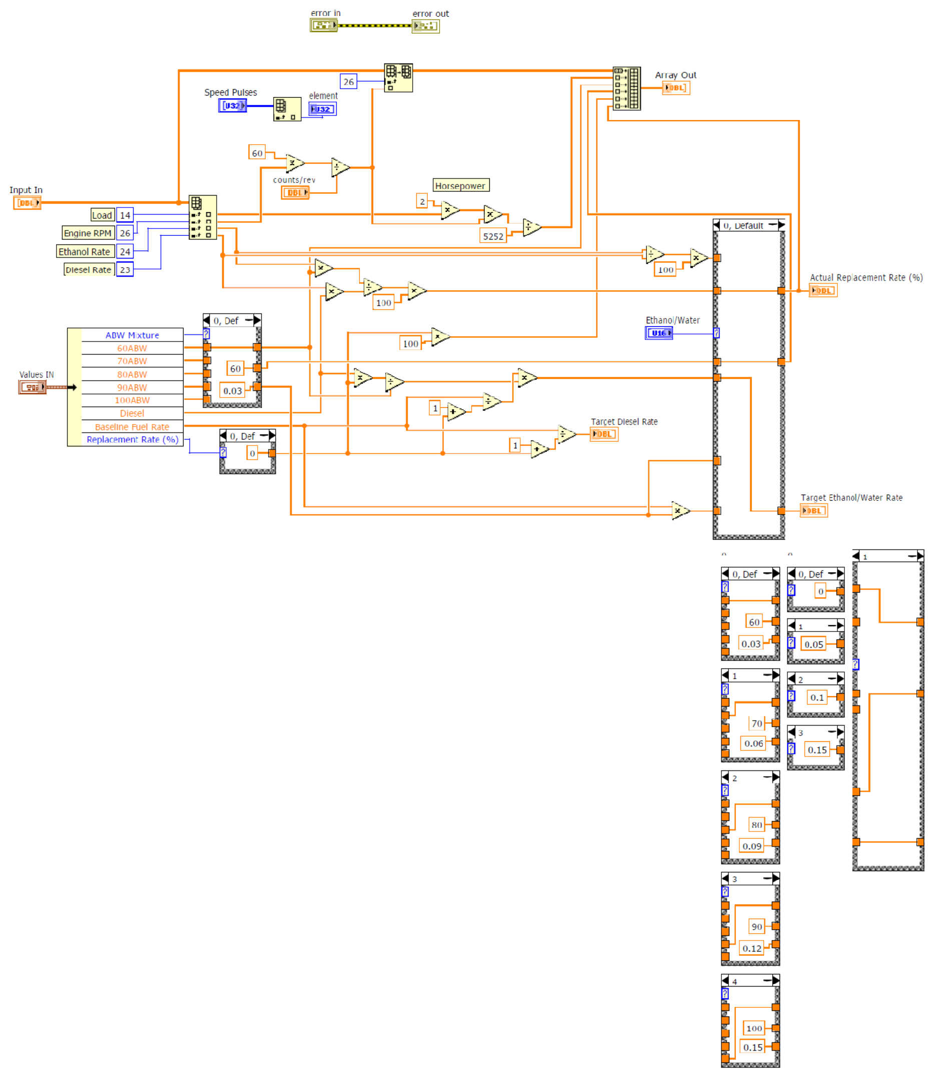
33	calculated	Actual R-Ratio
34	calculated	calc 6



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Connector Pane

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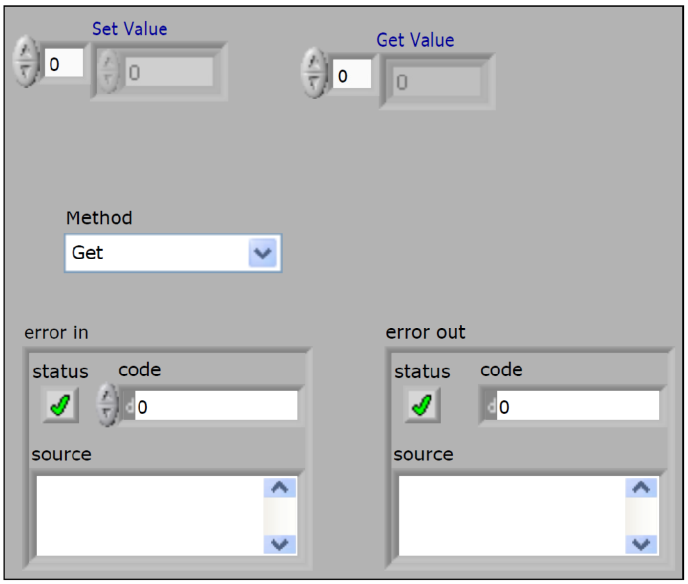

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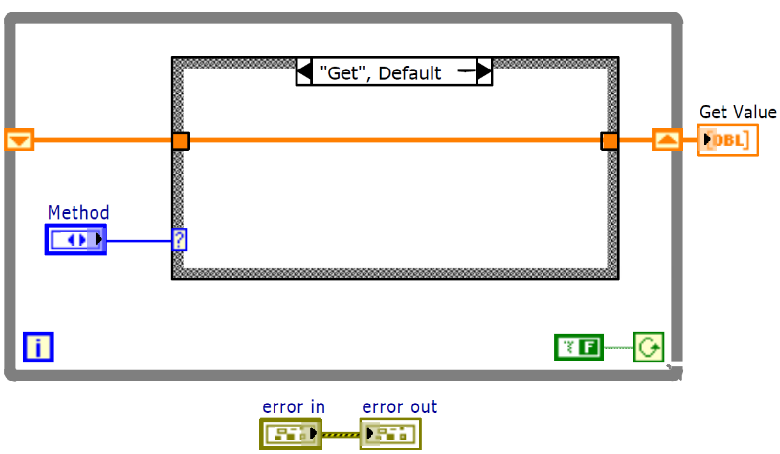

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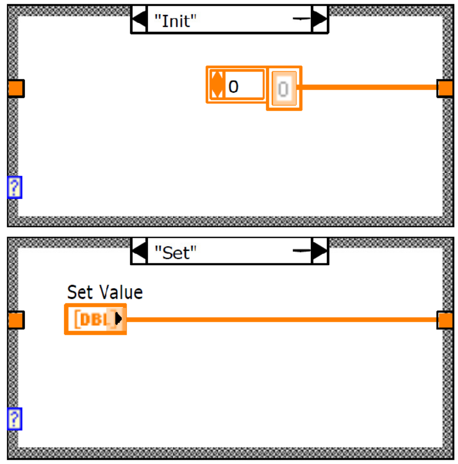

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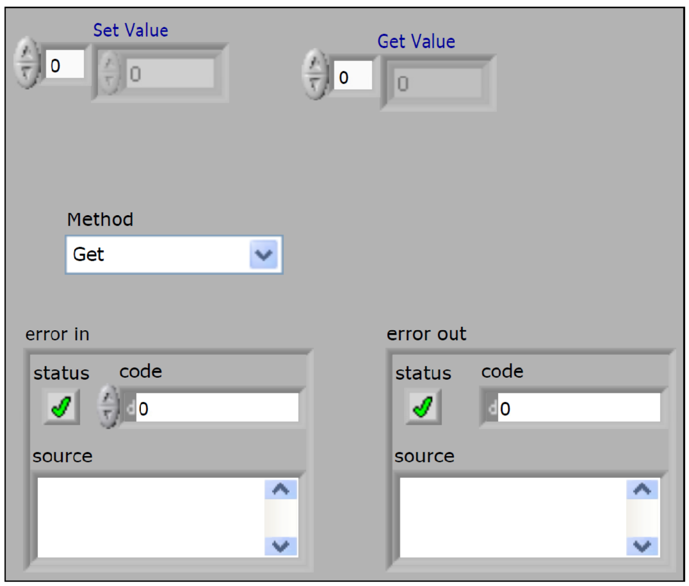

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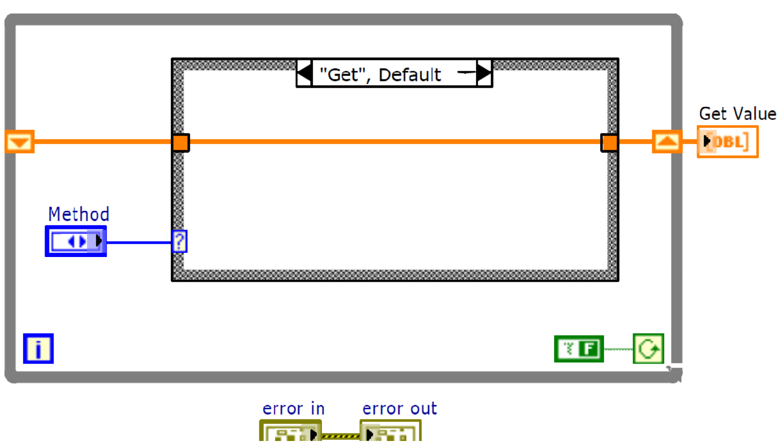

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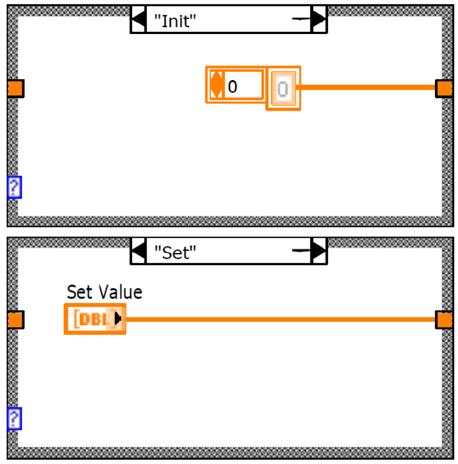

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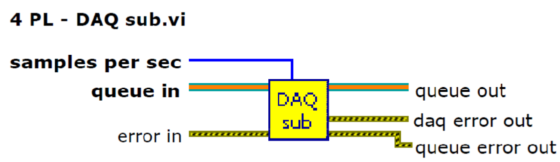

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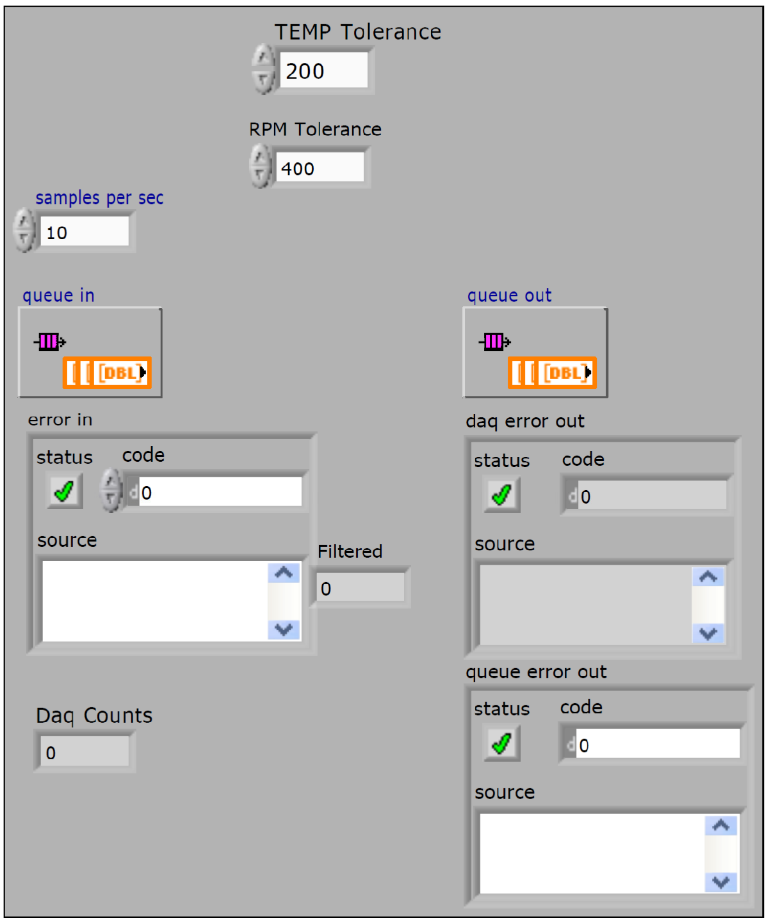

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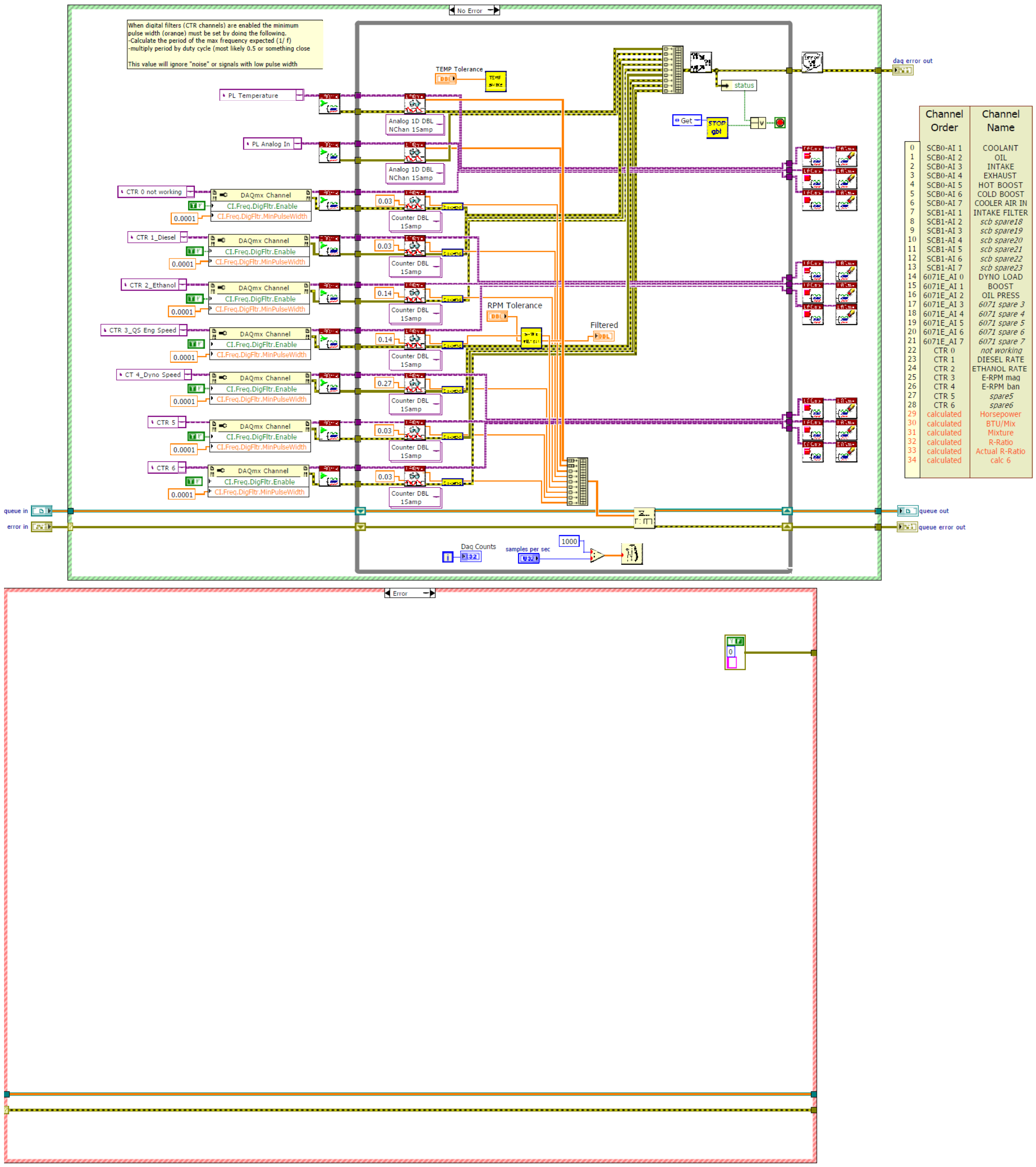

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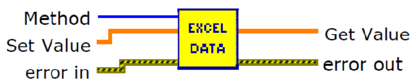

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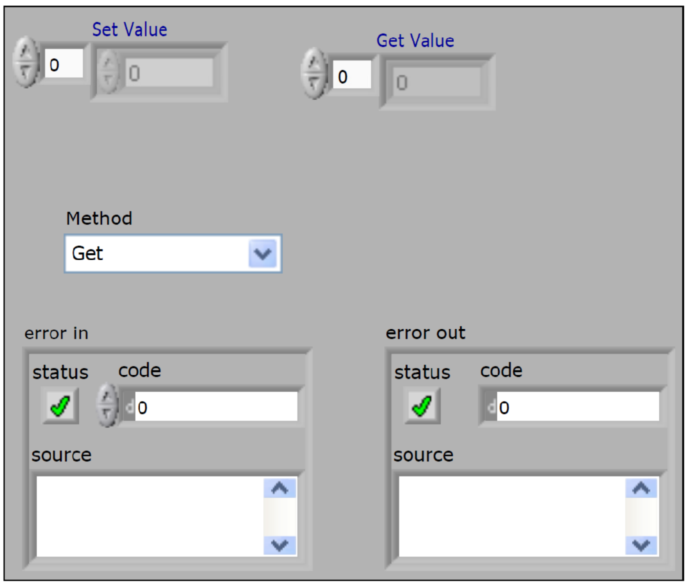

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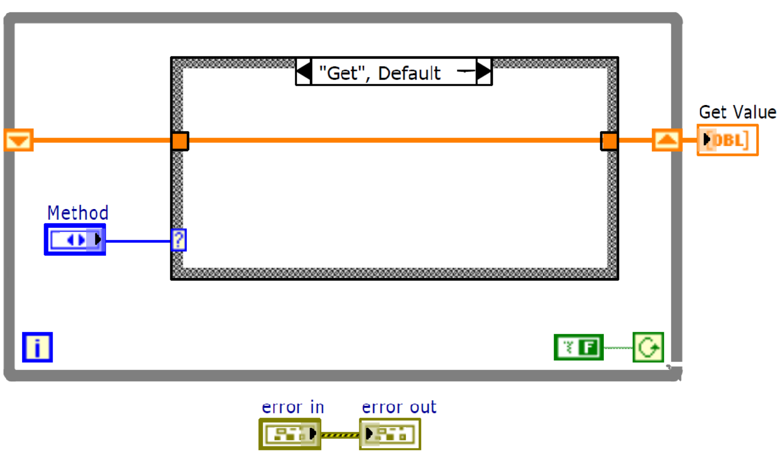

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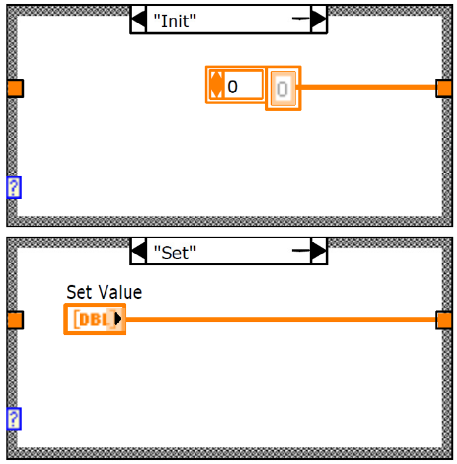

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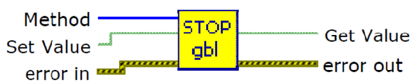
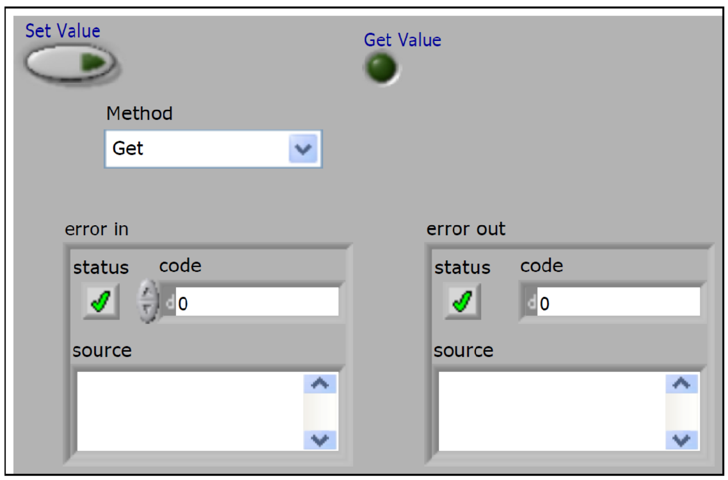
Connector Pane

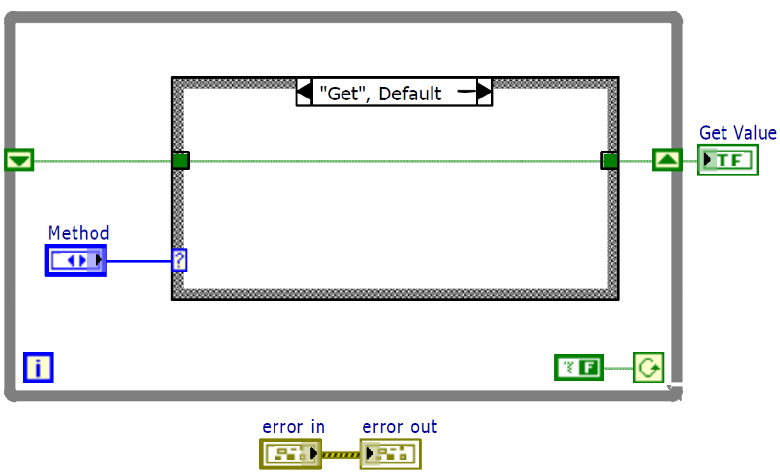
4 stop global.vi



Front Panel



Block Diagram



4 stop global.vi
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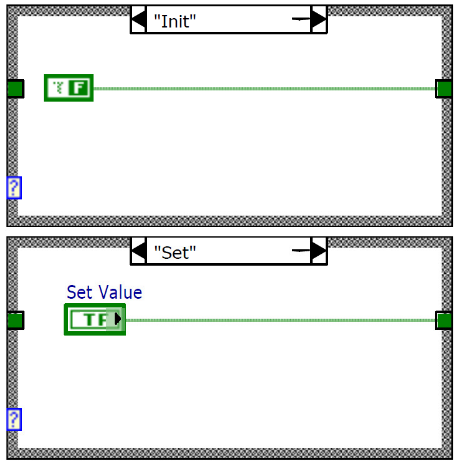

4 Temp Spike Filter.vi
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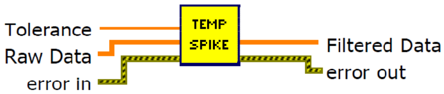
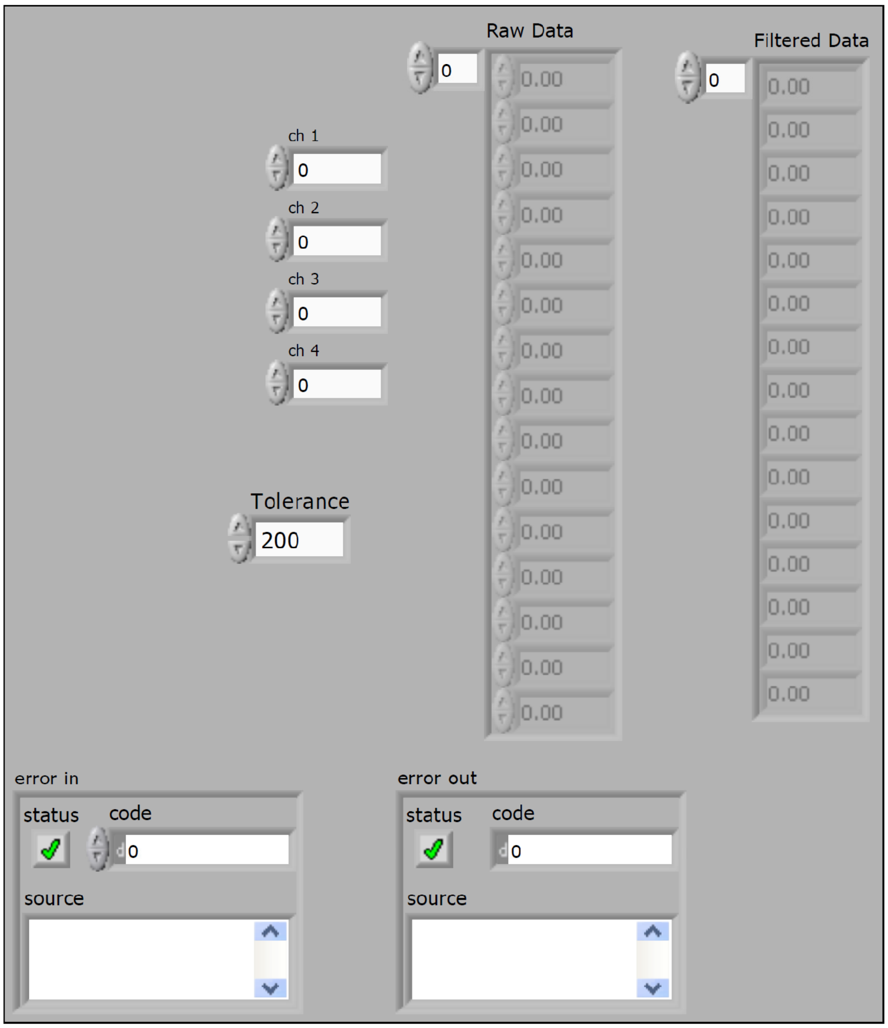
Last modified on 2/11/2010 at 8:18 AM
Printed on 7/14/2010 at 10:02 AM

Connector Pane

4 Temp Spike Filter.vi



Front Panel



Page 2

4 Temp Spike Filter.vi
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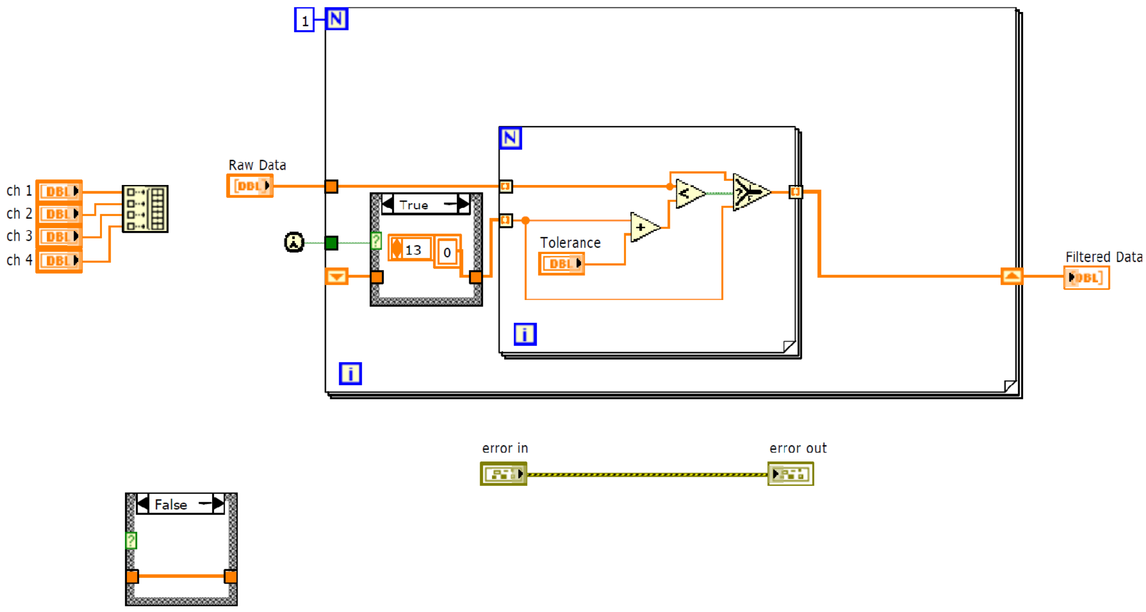
Last modified on 2/11/2010 at 8:18 AM
Printed on 7/14/2010 at 10:02 AM

Block Diagram



Page 1 

4 counter error handler.vi
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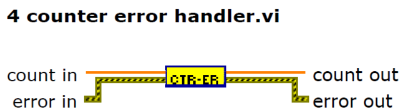
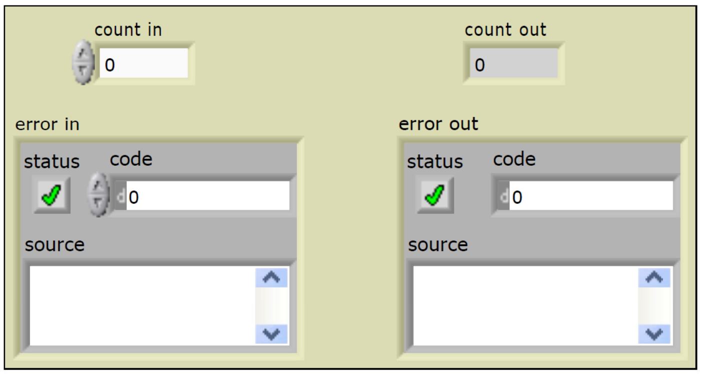
Printed on 7/14/2010 at 10:02 AM

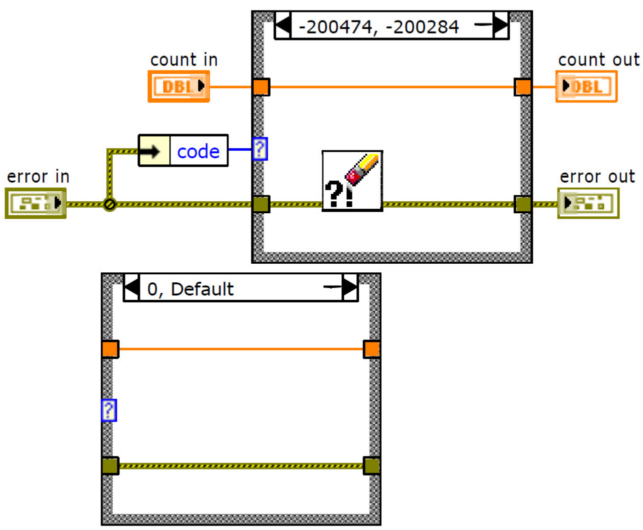
Connector Pane



Front Panel



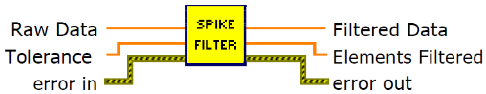
Block Diagram



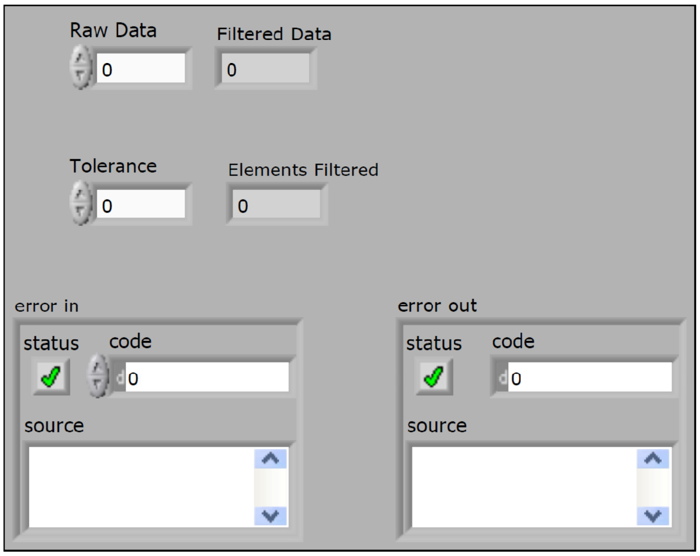
4 Spike Filter.vi
C:\Documents and Settings\Austin\My Documents\LabView VI's\PL rev4\4 Spike Filter.vi
Last modified on 2/10/2010 at 12:42 PM
Printed on 7/14/2010 at 10:02 AM

Connector Pane

4 Spike Filter.vi

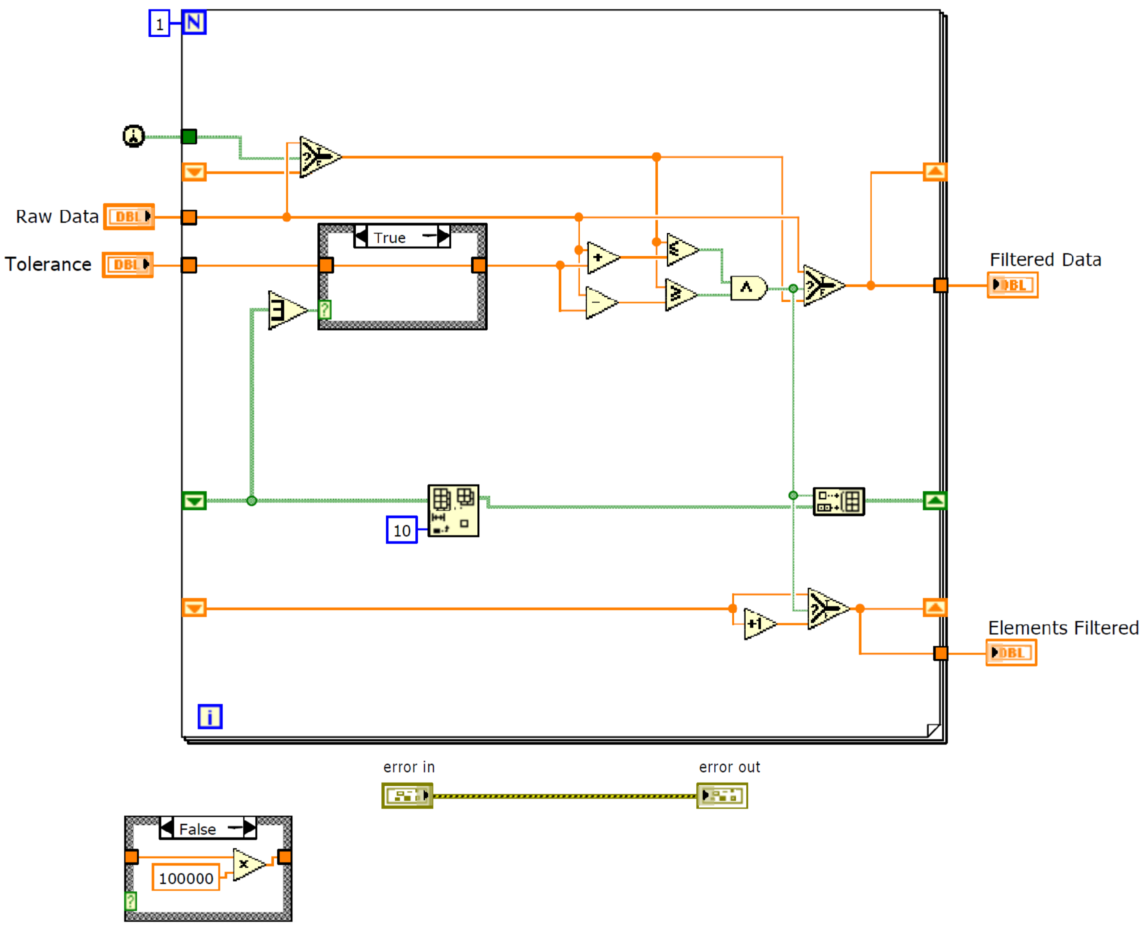


Front Panel



4 Spike Filter.vi
C:\Documents and Settings\Austin\My Documents\LabView VI's\PL rev4\4 Spike Filter.vi
Last modified on 2/10/2010 at 12:42 PM
Printed on 7/14/2010 at 10:02 AM

Block Diagram



Appendix E

Test Plan Matrix

		% Load																											
Blend	% Replacement	100							75							90							50						
60ABW	0	1200	1450	1956	1760	2200	1584	2400	1584	1450	1200	2200	1760	1956	2400	1584	1450	2400	1200	1956	2200	1760	2200	1584	1450	1760	1200	1956	2400
60ABW	5	1200	2200	1450	1584	1956	2400	1760	2200	1956	1450	1760	1200	1584	2400	2400	1584	2200	1200	1956	1450	1760	1760	1450	1200	1956	1584	2400	2200
60ABW	15	1584	1956	2200	1200	2400	1760	1450	1584	1450	2400	1956	1200	1760	2200	1450	1956	1200	2400	2200	1760	1584	1450	1956	1760	2400	1584	2200	1200
60ABW	10	2400	1956	1584	1200	1450	1760	2200	1450	2400	1200	1584	1956	2200	1760	1760	2400	1956	1450	1584	1200	2200	1450	2400	1584	1200	2200	1760	1956
100ABW	15	2200	1956	1200	1450	1584	2400	1760	2200	1450	1584	1760	1956	1200	2400	1956	2400	1584	1450	1760	1200	2200	1200	1760	1450	1584	1956	2400	2200
100ABW	0	1584	1450	2400	1200	1956	2200	1760	1956	1200	1450	2400	1584	1760	2200	1584	1956	2200	1200	2400	1450	1760	2200	1584	2400	1760	1956	1200	1450
100ABW	10	2400	1584	1956	1450	1760	1200	2200	1760	1956	2200	1200	1450	2400	1584	2200	1956	2400	1200	1584	1450	1760	2200	1760	1584	2400	1956	1450	1200
100ABW	5	1760	1584	2200	1956	1200	2400	1450	2200	1956	1584	1760	2400	1450	1200	1450	1760	2400	1584	2200	1956	1200	1200	1956	1450	2400	1760	1584	2200
80ABW	5	1956	2200	1450	2400	1584	1760	1200	1450	1760	1584	2400	2200	1200	1956	1956	2200	2400	1450	1760	1200	1584	2200	2400	1200	1760	1956	1450	1584
80ABW	15	1200	1956	1450	1584	2200	2400	1760	2400	1956	1584	1200	1760	1450	2200	2400	1200	2200	1450	1956	1584	1760	2400	1956	2200	1760	1584	1450	1200
80ABW	10	1760	1584	1450	2400	2200	1200	1956	1956	1584	2400	2200	1450	1200	1760	2200	1760	1584	1450	1200	1956	2400	1450	2400	1956	2200	1200	1584	1760
80ABW	0	1200	2400	1956	1584	1760	1450	2200	1200	2200	1584	1956	1760	2400	1450	2400	1200	1450	1760	2200	1956	1584	1760	1584	2200	1200	2400	1450	1956

Appendix F

Equations

Equations for Ethanol Fumigation of Diesel Engines – Dual Fuel Engine

Grant Janousek
February 2, 2010

Energy Balance Equation

$$(Dsl\ Baseline)*(Dsl\ LHV) = (Dsl_{w/eth})*(Dsl\ LHV) + (Eth_{mix})*(Eth\ LHV)$$

where Dsl Baseline, Eth_{mix} & $Dsl_{w/eth}$ have units of [lb/hr]
LHV = Lower Heating Value = [Btu/lb]
** $Dsl_{w/eth}$ = diesel flow to the engine while fumigation of ethanol mixture

Diesel Baseline Calculations for Reference

Used when determining baseline mass flow rate for reference during engine testing.

$$(Dsl\ Baseline) = (Dsl_{w/eth})*(1 + \%)$$

where % = decimal (example: 5% = 0.05)
Dsl Baseline has units of [lb/hr]
$Dsl_{w/eth}$ has units of [lb/hr]

Ethanol Mixture Flow Determination

- as a function of baseline diesel mass flow rate, %, diesel LHV & ethanol mixture LHV

$$Eth_{mix} = \frac{(DslBaseline)*(DslLHV)*(\%)}{(1+\%)*(EthLHV)}$$

where Dsl Baseline & Eth_{mix} have units of [lb/hr]
LHV = Lower Heating Value = [Btu/lb]
% = decimal (example: 5% = 0.05)

Appendix G

Power Lab Dynamometer Instructions

Power Lab Dynamometer Instructions

Start Up Procedure

1. Perform a visual inspection of engine and check fluid levels (oil, coolant).
2. Turn on breakers labeled *DYNAMATIC*.
3. Turn on water valve (yellow handle up is on).
4. Disengage the engine clutch.
5. Turn on exhaust fans (room and engine fans located on north wall).
6. Turn fuel pump switch on.
7. Turn *SPEED CONTROL* knob all the way clockwise.
8. Turn *CURRENT CONTROL* knob all the way counterclockwise.
9. Push black *EXCITATION ON* button.
10. Start engine.
11. Check for leaks and abnormal noises.
12. Engage clutch.
13. Warm up engine to normal operating temperature by following the engine operator's manual or the following sequence:

    A. Run engine for 2 minutes at 1200 rpm (no load).
    B. Run engine at 1200 rpm at 25% load until coolant temperature is above 100 °F.
    C. Run engine at 1500 rpm at 50% load until coolant temperature is above 135 °F.
    D. Run engine at 1800 rpm at 75% load until coolant temperature is above 170 °F or oil temperature is above 100 °F.

NOTES:
Read the engine operator's manual before starting.
Avoid excess idling.
Do not operate engine under full load until engine is to normal operating temperatures.
Never shut down a hot engine. If engine stops while under load, remove load and start immediately.

Shut Down Procedure

1. Remove all load.
2. Adjust engine rpm to 1200 rpm and run for 3-5 minutes to cool engine.
3. Disengage clutch.
4. Shut engine off.
5. Push red *EXCITATION OFF* button.
6. Shut water valve off.
7. Turn breakers off.
8. Turn exhaust fans off.

Appendix H

SAS Code:

Ethanol Emissions Analysis.sas
Ethanol Emission HC.sas
Ethanol Thermal Efficiency.sas
Water Analysis.sas

Ethanol Emissions Analysis.sas

```
* Code name:  Ethanol Emissions Analysis
*
* Author: Grant Janousek
* Last Revision: June 2, 2010
*
* Purpose:  To perform analysis on ethanol fumigation emissions.
;

options ls=112 pageno=1;
PROC IMPORT
DATAFILE="E:\Grad_Research\Engine_Data\Spring_2010_Ethanol_Averages_4.xls"
 /*PROC IMPORT DATAFILE="C:\Users\aparkhurst\Documents\AMP\CLIENTS\Hoy,
Roger\Grant Janousek\Engine_Data\Spring_2010_Ethanol_Averages_3.xls" */
OUT=ethanol DBMS=excel REPLACE;
*SHEET="SAS_Emissions";
SHEET="SAS_Em_NoOut";
RANGE="A1:AQ289"; * Make sure and change the range to the correct value if numbers
are added in above spreadsheet;
GETNAMES=yes;
run;

proc print data=ethanol;
run;

data ethanol_new;
set ethanol;
SqR_ratio= R_ratio*R_ratio;
*if Mixture = 60 and R_ratio = 0 then trt = 'A';
if Mixture = 60 and R_ratio = 5 then trt = 'B';
if Mixture = 60 and R_ratio = 10 then trt = 'C';
if Mixture = 60 and R_ratio = 15 then trt = 'D';
if Mixture = 80 and R_ratio = 0 then trt = 'E';
if Mixture = 80 and R_ratio = 5 then trt = 'F';
if Mixture = 80 and R_ratio = 10 then trt = 'G';
if Mixture = 80 and R_ratio = 15 then trt = 'H';
if Mixture = 100 and R_ratio = 0 then trt = 'I';
if Mixture = 100 and R_ratio = 5 then trt = 'J';
if Mixture = 100 and R_ratio = 10 then trt = 'K';
if Mixture = 100 and R_ratio = 15 then trt = 'L';

if 1150 < E_RPM_ban          < 1250 then speed = '1200';
if 1400 < E_RPM_ban          < 1500 then speed = '1450';
if 1534 < E_RPM_ban          < 1634 then speed = '1584';
if 1710 < E_RPM_ban          < 1810 then speed = '1760';
```

```
if 1906 < E_RPM_ban          < 2006 then speed = '1956';
if 2150 < E_RPM_ban          < 2250 then speed = '2200';
if 2350 < E_RPM_ban          < 2450 then speed = '2400';
run;

data ethanolGT15; set ethanol_new;
if  speed gt '1450';
run;

proc print data=ethanol_new; var Load Mixture R_ratio speed;
run;

*-----------------------------------------------------------------------;
*-------------------------Manometer Analysis----------------------------;
*-----------------------------------------------------------------------;

proc mixed data = ethanol_new covtest;
class Load trt speed;
model Manometer = trt speed trt*speed/ddfm=satterth;
random Load Load*trt;
lsmeans trt speed trt*speed;
lsmeans trt speed/pdiff;
run;

*-----------------------------------------------------------------------;
*-------------------------NOx Analysis----------------------------------;
*-----------------------------------------------------------------------;
* Run with SAS Emission File which includes 1200 rpm at 60ABW 15R
* Includes engine speeds set in ethanolGT15 data set;

proc mixed data = ethanolGT15 covtest;
class Load trt speed;
model NOx = trt speed trt*speed/ddfm=satterth;
random Load Load*trt;
lsmeans trt speed trt*speed;
lsmeans trt speed/pdiff;
run;

*Split-plot using trt factors;
proc mixed data = ethanolGT15  covtest;
class Load Mixture R_ratio speed;
model NOx = Mixture R_ratio speed/s ddfm=satterth;

        * No Mixture*R_ratio interaction found, so removed from model
  * model NOx = Mixture R_ratio Mixture*R_ratio speed /s ddfm=satterth;
```

```
random Load;
lsmeans Mixture R_ratio speed ;
lsmeans Mixture R_ratio speed/pdiff;
run;

*-----------------------------------------------------------------------;
*-------------------------NOx Analysis for 1200 rpm---------------------;
*-----------------------------------------------------------------------;

data ethanol1200; set ethanol_new;
if  speed = '1200';
run;
proc print data=ethanol1200; var NOx R_ratio speed;
run;

proc mixed data = ethanol1200;
class Load trt;
model NOx = trt/ddfm=satterth;
random Load Load*trt;
lsmeans trt;
lsmeans trt/pdiff;
run;

*Split-plot using trt factors;
proc mixed data = ethanol1200  covtest;
class Load Mixture R_ratio;
model NOx = Mixture R_ratio Mixture*R_ratio/s ddfm=satterth;

        * There is a Mixture*R_ratio interaction found;

random Load;
lsmeans Mixture R_ratio ;
lsmeans Mixture R_ratio/pdiff;
run;


*-----------------------------------------------------------------------;
*-------------------------NOx Analysis for 1450 rpm---------------------;
*-----------------------------------------------------------------------;

data ethanol1450; set ethanol_new;
if  speed = '1450';
run;
proc print data=ethanol1450; var NOx R_ratio speed;
run;
```

```
proc mixed data = ethanol1450 covtest;
class Load trt speed;
model NOx = trt/ddfm=satterth;
random Load Load*trt;
lsmeans trt;
lsmeans trt/pdiff;
run;

*Split-plot using trt factors;
proc mixed data = ethanol1450  covtest;
class Load Mixture R_ratio;
model NOx = Mixture R_ratio Mixture*R_ratio/s ddfm=satterth;

            * There is a Mixture*R_ratio interaction found;

random Load;
lsmeans Mixture R_ratio;
lsmeans Mixture R_ratio/pdiff;
run;


*----------------------------------------------------------------------;
*--------------------------HC Analysis---------------------------------;
*----------------------------------------------------------------------;

proc mixed data = ethanol_new covtest;
class Load trt speed;
model HC = trt speed trt*speed/ddfm=satterth;
random Load Load*trt;
lsmeans trt speed trt*speed;
lsmeans trt speed/pdiff;
run;

*Split-plot using trt factors;
proc mixed data = ethanol_new  covtest;
class Load Mixture R_ratio speed;
model HC = Mixture R_ratio Mixture*R_ratio speed /s ddfm=satterth;
  *model HC = Mixture R_ratio Mixture*R_ratio speed /s ddfm=satterth;
random Load Load*Mixture Load*R_ratio;
lsmeans Mixture R_ratio speed ;
lsmeans Mixture R_ratio speed/pdiff;
run;


*----------------------------------------------------------------------;
*--------------------------CO Analysis---------------------------------;
```

```
*-----------------------------------------------------------------------;


proc mixed data = ethanol_new;
class Load trt speed;
model CO = trt speed trt*speed/ddfm=satterth;
random Load Load*trt;
lsmeans trt speed trt*speed;
lsmeans trt speed trt*speed/pdiff;
run;

*Split-plot using trt factors;
proc mixed data = ethanol_new  covtest;
class Load Mixture R_ratio speed;
*model CO = Mixture R_ratio  speed Mixture*R_ratio/s ddfm=satterth;
  model CO = Mixture |R_ratio | speed /s ddfm=satterth;
*    model CO = Mixture |R_ratio  speed SPEED*MIXTURE SPEED*R_RATIO/s
ddfm=satterth;
random Load;
lsmeans Mixture;
*lsmeans Mixture| R_ratio speed SPEED*MIXTURE SPEED*R_RATIO;
lsmeans Mixture| R_ratio speed SPEED*MIXTURE SPEED*R_RATIO/pdiff;
run;


*-----------------------------------------------------------------------;
*---------------------------CO2 Analysis-----------------------------------;
*-----------------------------------------------------------------------;


proc mixed data = ethanol_new;
class Load trt speed;
model CO2 = trt speed trt*speed/ddfm=satterth;
random Load Load*trt;
lsmeans trt speed trt*speed;
lsmeans trt speed trt*speed/pdiff;
run;

*Split-plot using trt factors;
proc mixed data = ethanol_new  covtest;
class Load Mixture R_ratio speed;
model CO2 = Mixture R_ratio  speed Mixture*R_ratio/s ddfm=satterth;
  *model HC = Mixture R_ratio Mixture*R_ratio speed /s ddfm=satterth;
random Load;
lsmeans Mixture R_ratio ;
lsmeans Mixture| R_ratio /pdiff;
```

```
run;

*-----------------------------------------------------------------------;
*---------------------------O2 Analysis-----------------------------------;
*-----------------------------------------------------------------------;

proc mixed data = ethanol_new covtest;
class Load trt speed;
model O2 = trt speed trt*speed/ddfm=satterth;
random Load Load*trt;
lsmeans trt speed trt*speed;
lsmeans trt speed trt*speed/pdiff;
run;
proc mixed data = ethanol_new  covtest;
class Load Mixture R_ratio speed;
model O2 = Mixture R_ratio  Mixture*R_ratio speed/s ddfm=satterth;
  *model HC = Mixture R_ratio Mixture*R_ratio speed /s ddfm=satterth;
random Load;
lsmeans Mixture R_ratio ;
lsmeans Mixture |R_ratio /pdiff;
run;
```

Ethanol Emissions HC.sas

```
* Code name:  Ethanol Emissions HC
*
* Author: Grant Janousek
* Last Revision: May 25, 2010
*
* Purpose: The purpose of this code is to analyze the HC data with all 100% loads removed.  This will tell us if
* 50-90% loads are significicatly different than diesel only.  Note that 100% Load plotted gives inconclusive results.
;

options ls=112 pageno=1;
PROC IMPORT
DATAFILE="E:\Grad_Research\Engine_Data\Spring_2010_Ethanol_Averages_4.xls"
 /*PROC IMPORT DATAFILE="C:\Users\aparkhurst\Documents\AMP\CLIENTS\Hoy, Roger\Grant Janousek\Engine_Data\Spring_2010_Ethanol_Averages_3.xls" */
OUT=ethanol DBMS=excel REPLACE;
SHEET="SAS_Emissions_HC";
RANGE="A1:AQ217"; * Make sure and change the range to the correct value if numbers are added in above spreadsheet;
GETNAMES=yes;
run;

* proc print data=ethanol;
* run;

data ethanol_new;
set ethanol;
SqR_ratio= R_ratio*R_ratio;
if Mixture = 60 and R_ratio = 0 then trt = 'A';
if Mixture = 60 and R_ratio = 5 then trt = 'B';
if Mixture = 60 and R_ratio = 10 then trt = 'C';
if Mixture = 60 and R_ratio = 15 then trt = 'D';
if Mixture = 80 and R_ratio = 0 then trt = 'E';
if Mixture = 80 and R_ratio = 5 then trt = 'F';
if Mixture = 80 and R_ratio = 10 then trt = 'G';
if Mixture = 80 and R_ratio = 15 then trt = 'H';
if Mixture = 100 and R_ratio = 0 then trt = 'I';
if Mixture = 100 and R_ratio = 5 then trt = 'J';
if Mixture = 100 and R_ratio = 10 then trt = 'K';
if Mixture = 100 and R_ratio = 15 then trt = 'L';

if 1150 < E_RPM_ban          < 1250 then speed = '1200';
if 1400 < E_RPM_ban          < 1500 then speed = '1450';
```

```
if 1534 < E_RPM_ban        < 1634 then speed = '1584';
if 1710 < E_RPM_ban        < 1810 then speed = '1760';
if 1906 < E_RPM_ban        < 2006 then speed = '1956';
if 2150 < E_RPM_ban        < 2250 then speed = '2200';
if 2350 < E_RPM_ban        < 2450 then speed = '2400';
run;

* proc print data=ethanol_new;
* run;

*---------------------------------------------------------------------;
*----------------------HC Analysis w/out 100% Loads----------------------;
*---------------------------------------------------------------------;

proc mixed data = ethanol_new covtest;
class Load trt speed;
model HC = trt speed trt*speed/ddfm=satterth;
random Load Load*trt;
lsmeans trt speed trt*speed;
lsmeans trt speed/pdiff;
run;

*Split-plot using trt factors;
proc mixed data = ethanol_new  covtest;
class Load Mixture R_ratio speed;
model HC = Mixture R_ratio Mixture*R_ratio speed /s ddfm=satterth;
  *model HC = Mixture R_ratio Mixture*R_ratio speed /s ddfm=satterth;
random Load Load*Mixture Load*R_ratio;
lsmeans Mixture R_ratio speed ;
lsmeans Mixture R_ratio speed/pdiff;
run;
```

Ethanol Thermal Efficiency.sas

```
* Code name:  Ethanol Thermal Efficiency
*
* Author: Grant Janousek
* Last Revision: May 13, 2010
*
* Purpose:  To perform analysis on ethanol fumigation engine thermal efficiency.
;

PROC IMPORT
DATAFILE="E:\Grad_Research\Engine_Data\Spring_2010_Ethanol_Averages_2.xls"
OUT=ethanol DBMS=excel REPLACE;
SHEET="SAS_TE";
RANGE="A1:AK292"; * Make sure and change the range to the correct value if numbers
are added in above spreadsheet;
GETNAMES=yes;
run;

proc print data=ethanol;
run;

data ethanol_new;
set ethanol;
if Mixture = 60 and R_ratio = 0 then trt = 'A';
if Mixture = 60 and R_ratio = 5 then trt = 'B';
if Mixture = 60 and R_ratio = 10 then trt = 'C';
if Mixture = 60 and R_ratio = 15 then trt = 'D';
if Mixture = 80 and R_ratio = 0 then trt = 'E';
if Mixture = 80 and R_ratio = 5 then trt = 'F';
if Mixture = 80 and R_ratio = 10 then trt = 'G';
if Mixture = 80 and R_ratio = 15 then trt = 'H';
if Mixture = 100 and R_ratio = 0 then trt = 'I';
if Mixture = 100 and R_ratio = 5 then trt = 'J';
if Mixture = 100 and R_ratio = 10 then trt = 'K';
if Mixture = 100 and R_ratio = 15 then trt = 'L';

if 1150 < E_RPM_ban     < 1250 then speed = '1200';
if 1400 < E_RPM_ban     < 1500 then speed = '1450';
if 1534 < E_RPM_ban     < 1634 then speed = '1584';
if 1710 < E_RPM_ban     < 1810 then speed = '1760';
if 1906 < E_RPM_ban     < 2006 then speed = '1956';
if 2150 < E_RPM_ban     < 2250 then speed = '2200';
if 2350 < E_RPM_ban     < 2450 then speed = '2400';
run;
```

```
proc print data=ethanol_new;
run;

data ethanolGT15; set ethanol_new;
run;

proc print data=ethanolGT15; var NOx R_ratio speed;
run;

proc mixed data = ethanolGT15;
class Load trt speed;
model TE = trt speed trt*speed/ddfm=satterth;
random Load Load*trt;
lsmeans trt speed trt*speed;
lsmeans trt speed/pdiff;
run;

* Split-plot using trt factors;
proc mixed data = ethanolGT15  covtest;
class Load Mixture R_ratio speed;
model TE = Mixture R_ratio speed Mixture*R_ratio/s ddfm=satterth;
random Load;
lsmeans Mixture R_ratio speed ;
lsmeans Mixture R_ratio speed/pdiff;
run;


*--------------------------Original-----------------------------------;
proc mixed data = ethanol_new;
class Load trt speed;
model TE = trt speed trt*speed/ddfm=satterth;
random Load Load*trt;
lsmeans trt speed trt*speed;
lsmeans trt speed/pdiff;
run;
```

Water Analysis.sas

```
* Code name:  Water Analysis
*
* Author: Grant Janousek
* Last Revision: May 25, 2010
*
* Purpose:  To perform analysis on water fumigation results.
;

options ls=112 pageno=1;
PROC IMPORT
DATAFILE="E:\Grad_Research\Engine_Data\Spring_2010_Water_Averages.xls"
/* PROC IMPORT DATAFILE="C:\Users\aparkhurst\Documents\AMP\CLIENTS\Hoy,
Roger\Grant Janousek\Engine_Data\Spring_2010_Ethanol_Averages_3.xls"  ;*/
OUT=water DBMS=excel REPLACE;
SHEET="SAS_DataSet_Water";
RANGE="A1:AK34"; * Make sure and change the range to the correct value if numbers
are added in above spreadsheet;
GETNAMES=yes;
run;

* proc print data=water;
* run;

data water_new;
set water;

*if 1400 < Espeed < 1500 then speed = '1450';
*if 1906 < Espeed < 2006 then speed = '1956';
*if 2150 < Espeed < 2250 then speed = '2200';

if Load > 90;

run;


* proc print data=water_new; var NOx R_ratio Espeed;
* run;

*------------------------------------------------------------------------;
*--------------------------NOx Model-----------------------------------;
*------------------------------------------------------------------------;

Proc mixed data = water_new;
Model NOx = Espeed R_ratio/solution;
```

```
run;

Proc glm data = water_new;
Model NOx = Espeed R_ratio/solution;
run;

*---------------------------------------------------------------------;
*-------------------------HP Model---------------------------------;
*---------------------------------------------------------------------;

Proc mixed data = water_new;
Model Horsepower = Espeed R_ratio/solution;
run;

*---------------------------------------------------------------------;
*-------------------------TE Model---------------------------------;
*---------------------------------------------------------------------;

Proc mixed data = water_new;
Model TE = Espeed R_ratio/solution;
run;

*---------------------------------------------------------------------;
*-------------------------HC Model---------------------------------;
*---------------------------------------------------------------------;

Proc mixed data = water_new;
Model HC = Espeed R_ratio/solution;
run;

*---------------------------------------------------------------------;
*-------------------------CO Model---------------------------------;
*---------------------------------------------------------------------;

Proc mixed data = water_new;
Model CO = Espeed R_ratio/solution;
run;

*---------------------------------------------------------------------;
*-------------------------CO2 Model--------------------------------;
*---------------------------------------------------------------------;

Proc mixed data = water_new;
Model CO2 = Espeed R_ratio/solution;
run;
```

```
*-----------------------------------------------------------------------;
*--------------------------O2 Model----------------------------------;
*-----------------------------------------------------------------------;

Proc mixed data = water_new;
Model O2 = Espeed R_ratio/solution;
run;
```